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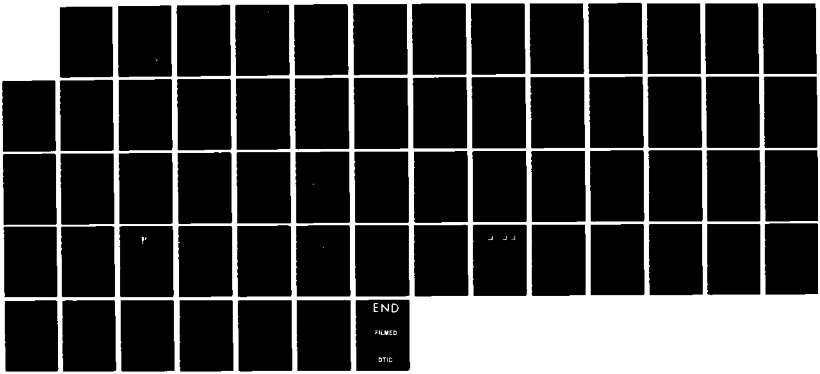

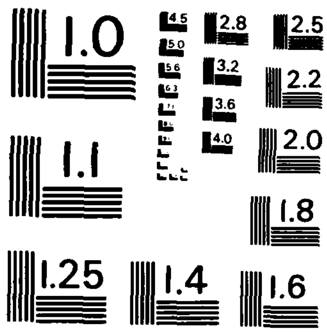

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SIMULATED GROUND RESPONSE USING NON-LINEAR ELASTIC MODULI

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Vincent J. Murphy

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AIR FORCE SYSTEMS COMMAND
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This report discusses procedures for the extrapolation of low-strain seismic measurements made at a specific site to predict the site response under earthquake loading conditions. Because of the non-linear relation between stress and strain exhibited by soils at strain levels exceeding about 10^{-6}, a program to determine dynamic soil properties at low to high strain levels and at different depths in the soil column at the site is required. Utilizing recent advances in field measurement techniques, this goal can be best accomplished with a combination of in situ geophysical methods, including surface reflection and refraction methods; cross-hole and down-hole techniques utilizing impulsive and vibratory sources; and dynamic loading methods involving monitoring of in-place deformation. Knowledge of the variation with strain level and other factors of equivalent moduli and damping at a site may enable frequency-dependent scaling rules to be developed for the computation of high-strain response from microseismic response curves. This procedure can be evaluated by performing field measurements at sites for which comprehensive strong motion data bases are already available.

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SUMMARY

This project is concerned with the development of improved techniques for prediction of site-specific dynamic soil response under earthquake- or blast-induced loading. Specifically, the project addresses the design of improved field techniques for in situ determination of dynamic soil properties under varying conditions of strain level, duration of shaking, cyclic loading, fluid saturation level, and effective stress; and how the field measurements may be used to predict the high strain site response from measurements of low level seismic activity.

This report presents the results of Phase I of the project, in which the feasibility of achieving this goal was considered.

A direct estimate of site response at a particular site can be obtained by analysis of records of strong ground motion obtained at the site from earthquakes of different magnitudes and epicentral distances. However, at most sites the necessary strong motion data base is not available. The suggestion has therefore been made that analysis of microseismic activity, which is available for most sites, could be used instead to establish an amplification factor under low level loading and adjustments made to this amplification factor to account for the non-linear behavior of soils at high strains. In order to do this, information on the dynamic properties of soils at the site under low to high strain levels (10^{-6} to 10^{-3}) is required.

In order to determine the dynamic behavior of soils, both laboratory techniques and in situ methods can be employed. Laboratory methods, however, suffer from problems of interpretation due to sample disturbance and relaxation of the in situ state of stress upon removal of the sample from

the soil column. We have therefore concentrated upon investigating in situ methods for determination of shear modulus and damping as a function of strain level.

Within the last 10 years, several advances in in situ techniques have now made it feasible to measure dynamic soil properties in place under varying conditions of strain level, effective stress, and duration and frequency of loading. The cross-hole technique with a guided weight-drop source and receiver holes drilled from two to twenty feet from the source hole, allows strain levels from 10^{-6} to 10^{-3} to be achieved. Borehole shear devices or dynamic screwplate arrangements also allow determination of in situ dynamic soil properties at high strains as a function of depth. The hydraulic VSP technique may provide information on the relative permeability of different layers within the soil column.

As a result of our investigations during Phase I of this project, we conclude that a feasible field program to determine dynamic soil properties under earthquake loading conditions can be achieved. In developing the field methods, sites will be chosen at which extensive previous sampling and investigations have been performed. In order to address the question of applying the field measurements to microseismic site response, we will also conduct investigations at sites in the Western U.S. for which existing strong motion and microseismic data bases are available. By comparing the observed strong motion data at the sites with predictions made on the basis of the microseismic measurements and the measured dynamic soil properties, we will obtain a direct check on the validity of our method.

PREFACE

This report was prepared by Weston Geophysical Corporation under the direction of Mr. Vincent J. Murphy, Vice-President of Weston and Principal Investigator on the project. Dr. Glyn M. Jones, Senior Staff Consultant at Weston and Assistant Project Scientist on the project, was responsible for the literature review and preparation of the report. Other members of Weston's senior staff who contributed to discussions on in situ methods of testing are Mr. Richard J. Holt and Mr. Edward N. Levine.

We are grateful to Dr. Mishac Yegian, Associate Professor and Chairman of the Department of Civil Engineering at Northeastern University, who reviewed the report and provided valuable input during various phases of the study.

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1. BACKGROUND OF PROBLEM

Prediction of the response of a soil column to earthquake- or blast-induced vibrations is a critical element in the efficient design of structures on soil that will be able to withstand the ground vibrations resulting from these events. The level and characteristics of the soil disturbance will generally depend in a complicated manner upon factors such as the propagation path; the interaction of the soil and the underlying bedrock; and on the dynamic properties of the soil column itself.

Three different approaches to the prediction of site response, listed by level of increasing complexity, are to:

(1) Analyze strong ground motion records recorded at the site.

(2) Measure response to microseismic activity and obtain an amplification factor relative to hard rock sites.

(3) Investigate stress-strain relation for soil at the site and use computer codes to predict the site response for a given event.

At sites for which strong motion records from a number of previous earthquakes have been recorded, analysis of the records from earthquakes of different magnitudes and epicentral distances might provide a basis for predicting the ground motion following possible future events. Figure 1a displays velocity response spectra from earthquakes of increasing magnitude recorded at a site at Hososhima, Japan (Tokimatsu and Midorikawa[1]). Velocity response spectra represent the response to the measured ground motion for different earthquakes (e.g. Figure 1b) of a single degree-of-freedom system with varying natural periods and a specified amount of critical damping (5% in this case). Response spectra computed in this manner are a convenient way of comparing different source records.

---

1. Tokimatsu, K., and Midorikawa, S. (1981) Nonlinear soil properties estimated from strong motion accelerograms, Proc. Intl. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri:117-122.

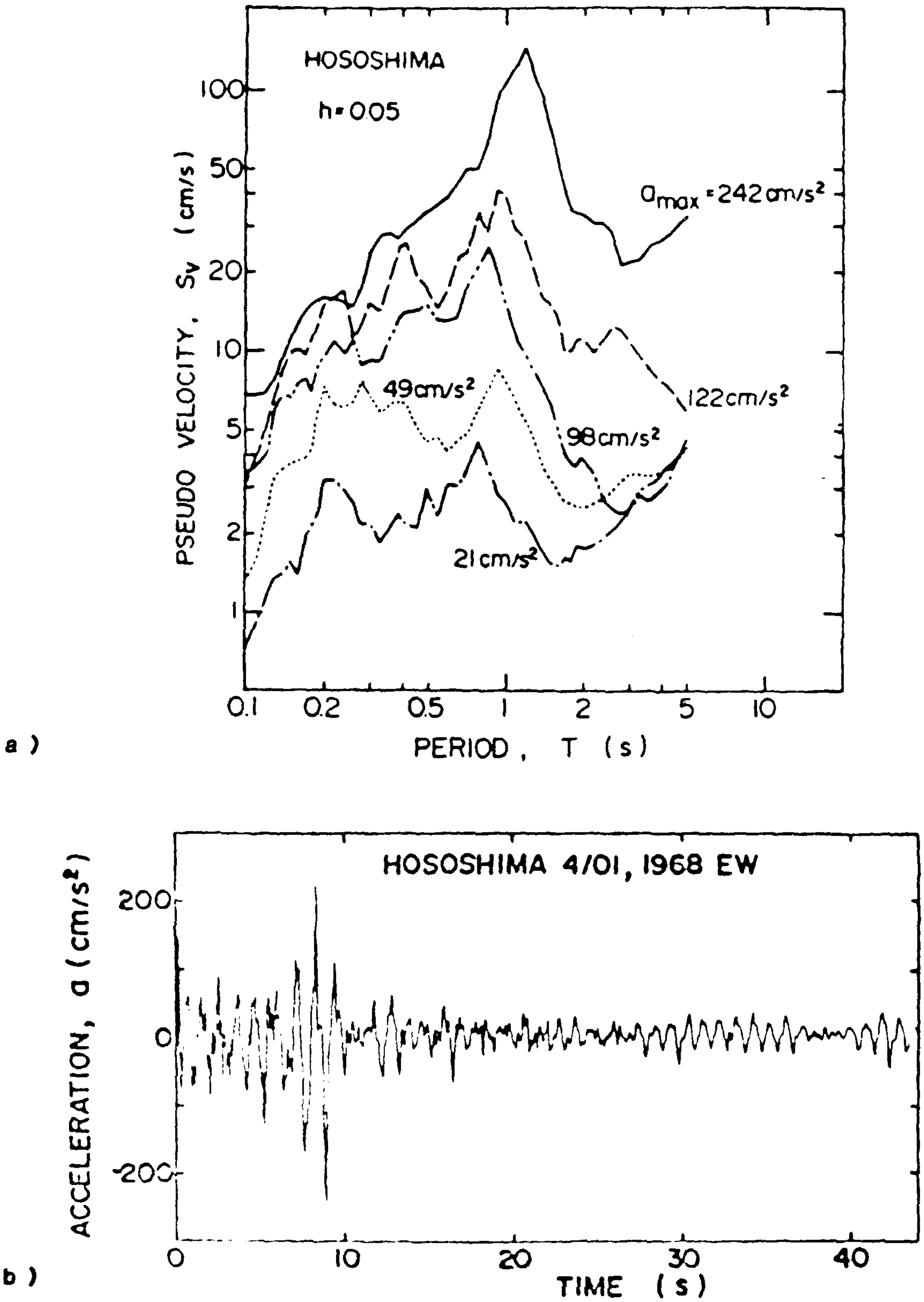

Figure 1. (a) Velocity Response Spectra for earthquakes of increasing magnitude recorded in Japan (b) Time record of typical earthquake (Tokimatsu and Midorikawa[1]).

The response spectra shown in Figure 1a are similar in shape but the predominant spectral peak generally increases in period as the peak acceleration increases. Figure 2 schematically depicts the change in damping ratio and secant shear modulus (defined in Section 2), observed in soils as a function of increasing strain level, that is responsible for this behavior. As the strain level increases above about 10^{-6}, the shear modulus of soils decreases because of non-linear behavior, and therefore the fundamental period of vibration increases. At the same time there is an increase in absorption of energy, or damping.

If response spectra were available for a variety of earthquake types at a given site, it would be a relatively simple matter to predict the response to a hypothetical future event by interpolation. The problem is that this strong motion data base is not available for most sites. Less direct means of estimating site response must therefore be found.

Another method that has been proposed for site response evaluation is to monitor the ground motion at a site due to low level microseismic activity. Microseisms can be generated in a number of ways: by wave action on a nearby coastline due to passage of cold fronts; by distant earthquakes; or even by events such as quarry blasting or traffic-generated noise. Most sites can therefore rely upon a certain amount of microseismic activity, analysis of which might provide a clue to the nature of the dynamic soil response.

Figure 3 shows response curves determined at six different sites from analysis of the ground motions from distant earthquakes (Seed and Idriss[2]). The soil columns can be graded from relatively stiff (high shear modulus - Site A) to relatively soft (low shear modulus - Site F), corresponding to decreasing proportions of sand or gravel and increasing proportions of clay and silt (see Figure 9). Corresponding to the change in soil type, we can see that the fundamental period of vibration increases as the shear modulus decreases. Thus response spectra derived from microseismic activity reflect the different values of shear modulus at these particular sites.

---

2. Seed, H.B., and Idriss, I.M. (1969) Influence of soil conditions on ground motions during earthquakes, J. Am. Soc. Civ. Engrs., Soil Mech. Found. Div., 93(No. SM1):99-137.

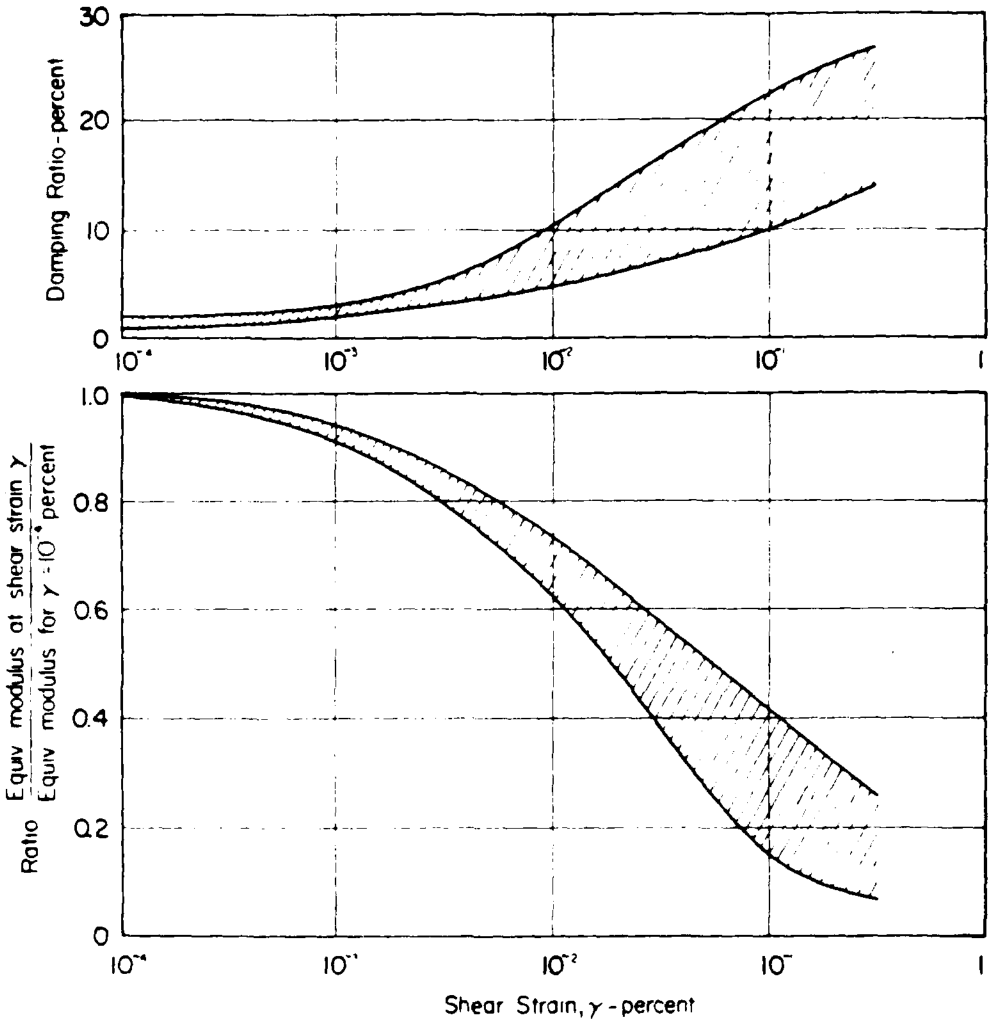

Figure 2. Influence of shear strain on equivalent modulus and damping ratio (Seed[5]).

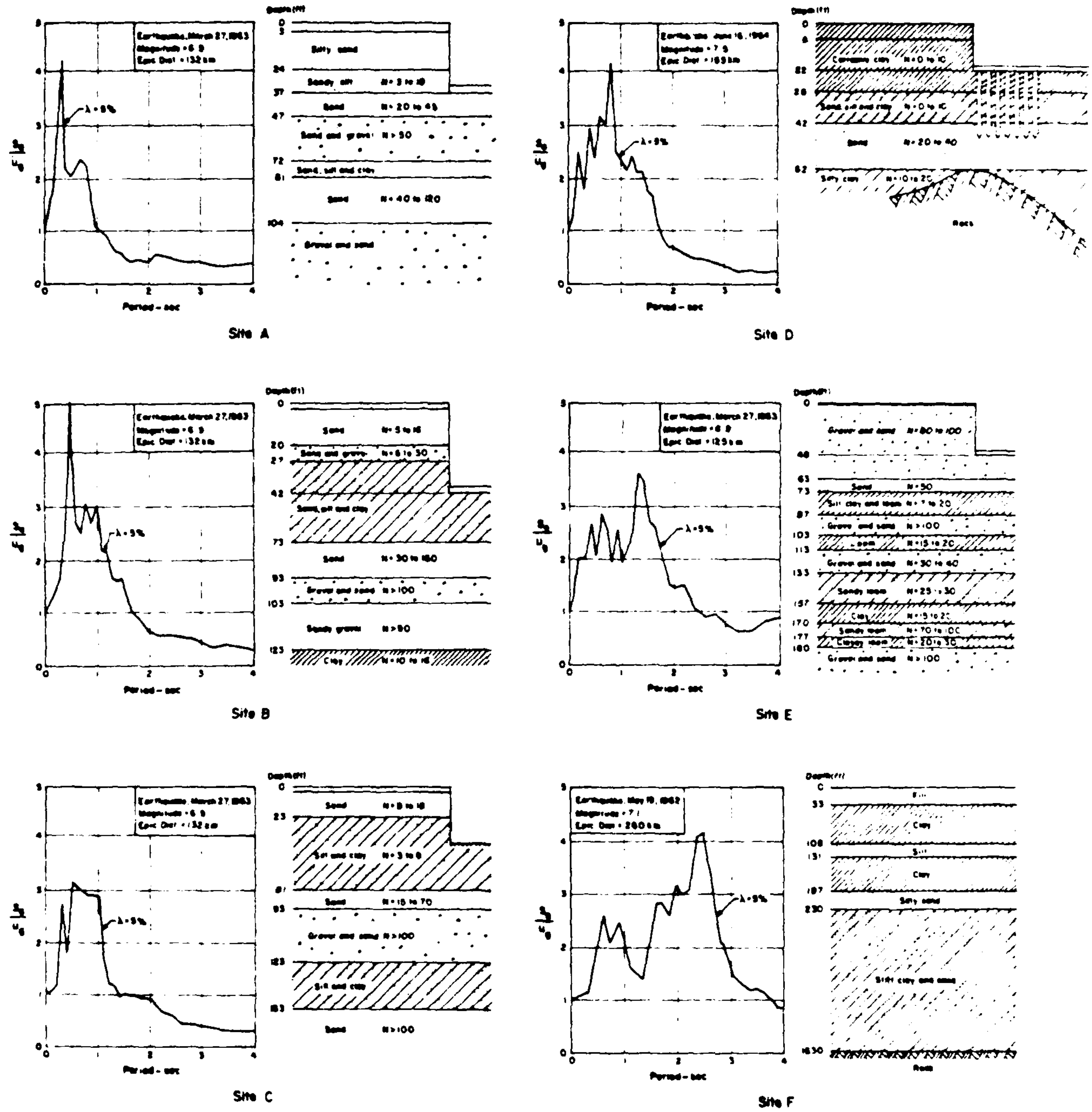

Figure 3. Effect of soil conditions on form of response spectra (Seed[5]).

The ratio of spectra of microtremors recorded on a soft soil site and on an adjacent hard rock site can also be used to define a frequency-dependent ground amplification factor which is apparently independent of the type of microtremor source (Akamatsu[3]) and which correlates with the degree of damage observed due to nearby earthquakes (Espinoza and Algermissen[4]). This suggests that a useful criterion of damage potential at a site might be the ground amplification factor determined from microseismic monitoring.

The problem at present with using measurements of microseismic activity to estimate the dynamic response of a site under a hypothetical future event is that the dynamic properties of soil show a complicated non-linear dependence on strain level and other factors.

In general, soils amplify ground motions transmitted through the crust from nearby events. Figures 4a and 4b show, however, two examples of sites at which surface accelerations actually decrease as the base motion increases (Seed[5]). This result is attributed to the existence of highly attenuating surface layers at these particular sites. These examples illustrate that in order to use measured microseismic activity to infer the dynamic site response under strong loading conditions, detailed information on the non-linear behavior of soil at the site is required.

This leads us to the third method for predicting dynamic site response, which is to perform a multi-stage analysis procedure which ideally includes:

- Detailed sampling and classification of the soil column at the site.
- Performance of comprehensive tests to determine the dynamic properties of the soil under a wide range of loading conditions.
- Incorporation of the dynamic response characteristics of the soil into computer codes which, given an assumed input signal at the base of the soil column, will compute the motion at any other depth (Figure 5).

---

3. Akamatsu, J. (1984) Seismic amplification by soil deposits inferred from vibrational characteristics of microseisms, Bull. Disast. Prev. Inst., Kyoto University 34(Pt. 3)(No. 306):105-127.

4. Espinosa, A.F., and Algermissen, S.T. (1972) Soil amplification studies in areas damaged by the Caracas earthquake of July 29, 1967. Paper presented at the International Conference on Microzonation, Seattle, Washington.

5. Seed, H.B. (1969) The influence of local soil conditions on earthquake damage. Preprint of paper presented at 7th Intl. Conf. on Soil Mechanics and Foundation Engineering, Mexico City.

a)

b)

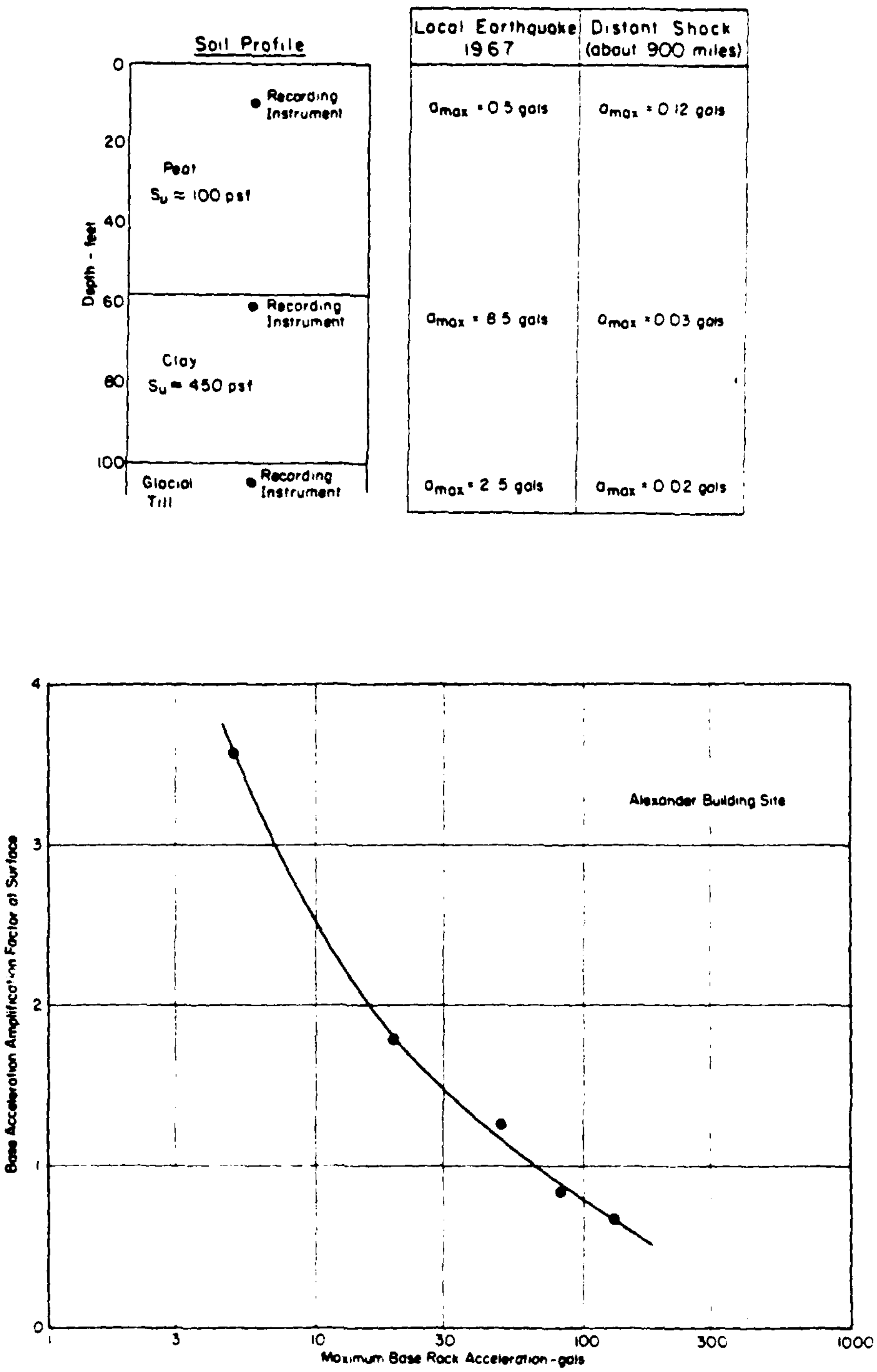

Figure 4. (a) Maximum ground accelerations recorded in Union Bay, Seattle (b) Variations of amplification factor with maximum base rock acceleration (Seed[5]).

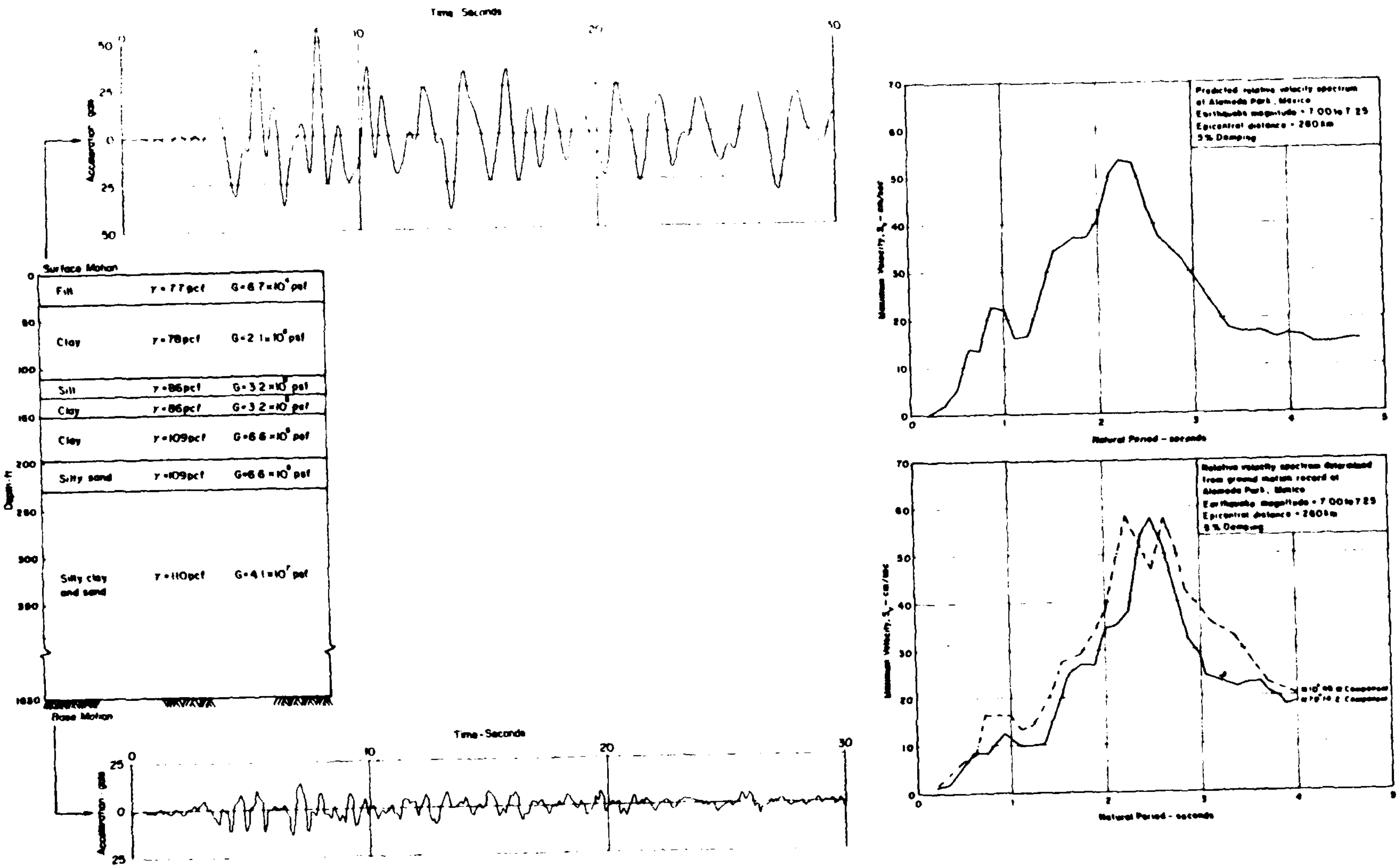

Figure 5. Analysis of soil response at site in Alameda Park, Mexico City (Seed[5]).

Besides strain level, some of the other factors which control the dynamic behavior of soils are:

- Void Ratio
- Number of Cycles of Loading
- Rate of Loading
- Loading Path
- Effective Mean Principal Stress
- Fluid Saturation Level
- Drainage Characteristics
- Consolidation Effects

These factors enter into the dynamic response of the soil column by modifying the stress-strain relation in various ways. Under repetitious cyclic loading, for example, pore pressure buildup can occur in cohesionless saturated soils, resulting in a decrease in effective stress and, in extreme cases, in a complete loss of shear strength (e.g. Seed & Lee[6]). Laboratory tests suggest that the rate of loading may also affect the ultimate strength of saturated cohesive soils (Richart et al[7]). It is therefore important that the soils be tested over as wide a range of loading conditions as possible.

Three different methods for analyzing the dynamic properties of soils are:

(1) From laboratory measurements on selected soil samples.

(2) In situ using geophysical methods.

(3) From empirical procedures using low-strain soil parameters obtained from field tests.

Current techniques used to predict the non-linear behavior of soils under high strain conditions rely heavily upon the use of empirical curves derived from laboratory tests. Typically, low strain field measurements of elastic moduli are used to fix a starting point on an empirical curve which is then used to infer the soil behavior at higher strains.

---

6. Seed, H.B., and Lee, K.L. (1966) Liquefaction of saturated sand during cyclic loading, J. Am. Soc. Civ. Engrs., Soil Mech. Found. Div. 92(No.SM6):105-134.

7. Richart, F.E., Hall, J.R., and Woods, R.D. (1970) Vibrations of Soils and Foundations, Prentice-Hall, New Jersey.

The reason for this approach is that, in the laboratory, various test parameters, such as strain level, cycles of loading, etc., can be more easily controlled and varied over wider ranges than under in situ conditions. However, a major disadvantage with using laboratory data to infer the dynamic property of soils is that the samples are often disturbed during collection, with the result that the moduli values determined using laboratory and field techniques often differ by a factor of 2 or more at the same strain level (Figure 6 - Fugro[8]).

Because of these differences, low strain field measurements are therefore used to adjust the laboratory curve of modulus versus strain, the assumption being that the differences between laboratory and field data observed at low strains are typical of all strains. This assumption has not been quantified by performing in situ tests at higher strain amplitudes.

It is becoming increasingly obvious that improved in situ field testing methods are needed to avoid problems of sample disturbance in laboratory testing. In order to be useful, these methods should provide dynamic moduli under the following conditions:

- At strain levels ranging from 10^{-6} to 10^{-3}.
- For different soil types.
- Under varying cycles and frequencies of loading.
- Under different degrees of fluid saturation.
- At various levels of effective stress.

In addition, the in situ methods should also provide an estimate of damping ratio under field conditions.

This report presents a discussion of the feasibility of developing these in situ techniques. Section 2 discusses the form of the stress-strain relation for soils and defines some common terms. In Sections 3 and 4, current techniques for laboratory and in situ testing of soils are reviewed. Finally, Section 5 evaluates the technical feasibility of performing high strain in situ measurements, and how these may be used in conjunction with microseismic

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8. Fugro, Inc. (1978) Evaluation of In Situ Testing Methods for High-Amplitude Dynamic Property Determination, EPRI NP-920, Final Report to Electric Power Research Institute.

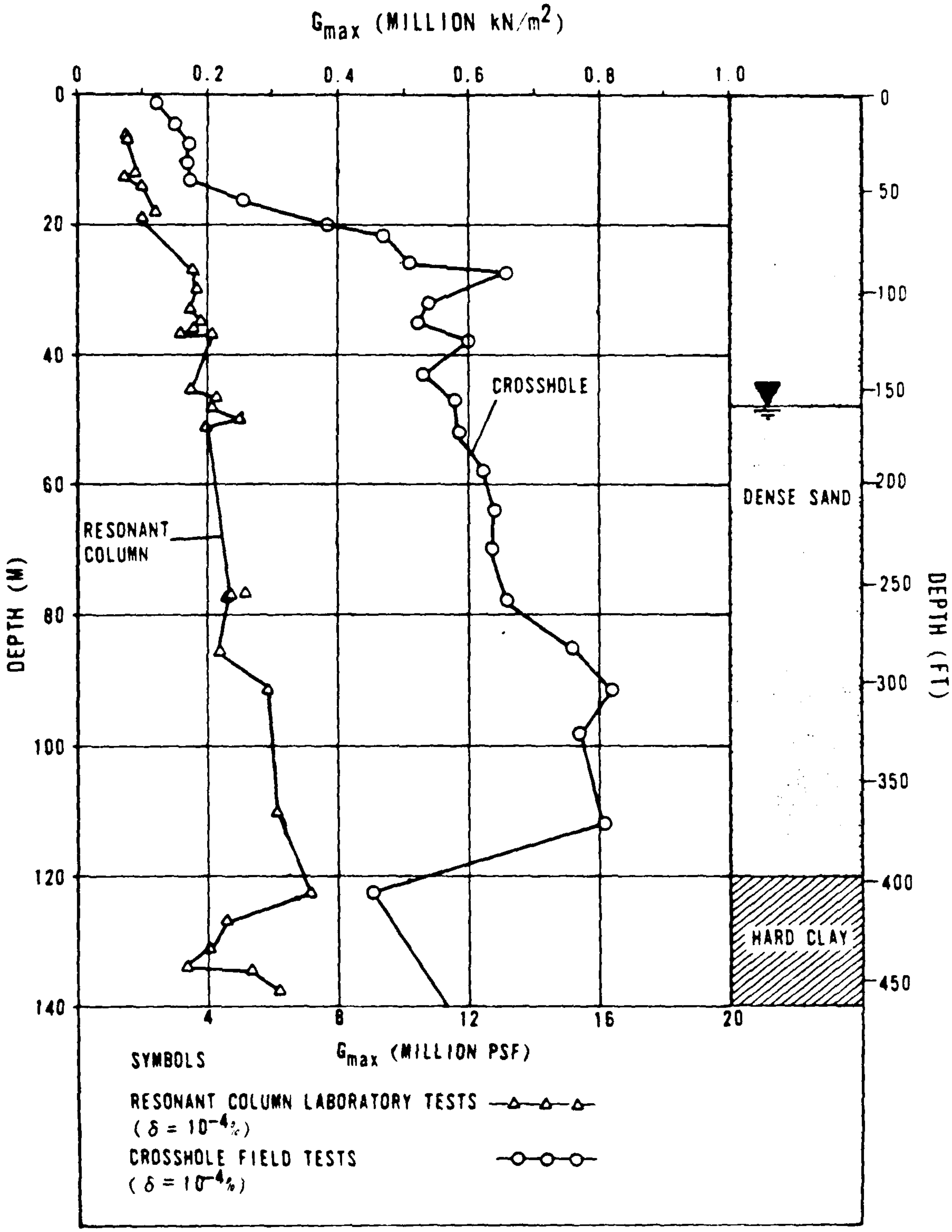


Figure 6. Comparison of low strain shear moduli determined using laboratory and in situ testing methods (Fugro*).

measurements, to enhance current techniques for dynamic soils response. The development of improved in situ measurements in coordination with analysis of microseismic measurements will form the basis for our Phase II proposal.

2. THE STRESS-STRAIN RELATION FOR SOILS

The response of a soil column to a high-energy propagating disturbance is primarily governed by the variation of moduli and damping factor with strain level. Figure 7a shows the shape of the stress-strain curve for soils loaded under increasing shear stress with a constant restraining boundary pressure (Yoshimi et al[9]). The shape of this curve is considered representative of the behavior of soils in situ under low to high shear strain loading.

At very low values of strain, the initial portion of the curve may be approximated by a linear elastic stress-strain relation of the form:

$$\tau = G\gamma \tag{1}$$

where

τ = shear component of the stress tensor

γ = shear component of the strain tensor

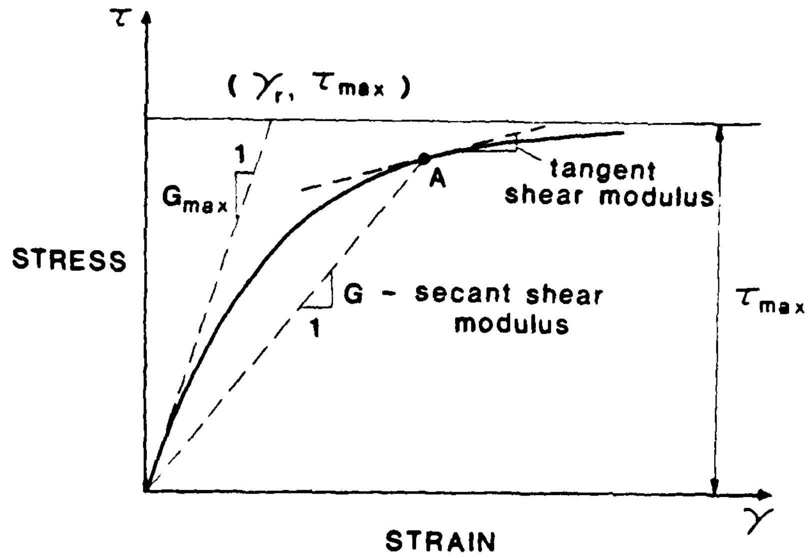
G = shear modulus

As the stress increases, the stress-strain curve becomes non-linear (Figure 7a), with a hyperbolic shape that may be approximated by the relation (Hardin and Drnevich[10]):

---

9. Yoshimi, Y., Richart, F.E., Prakash, S., Barkan, D.D., and Ilyichev, V.A., (1977) Soil dynamics and its application to foundation engineering, Proc. 9th Intl. Conf. on Soil Mechanics and Foundation Engineering, Tokyo 2:605-650.

10. Hardin, B.O. and Drnevich, V.P. (1972) Shear modulus and damping in soils: Design equations and curves, J. Am. Soc. Civ. Engrs., Soil Mech. Found. Div. 98 (No. SM 7): 667-692.



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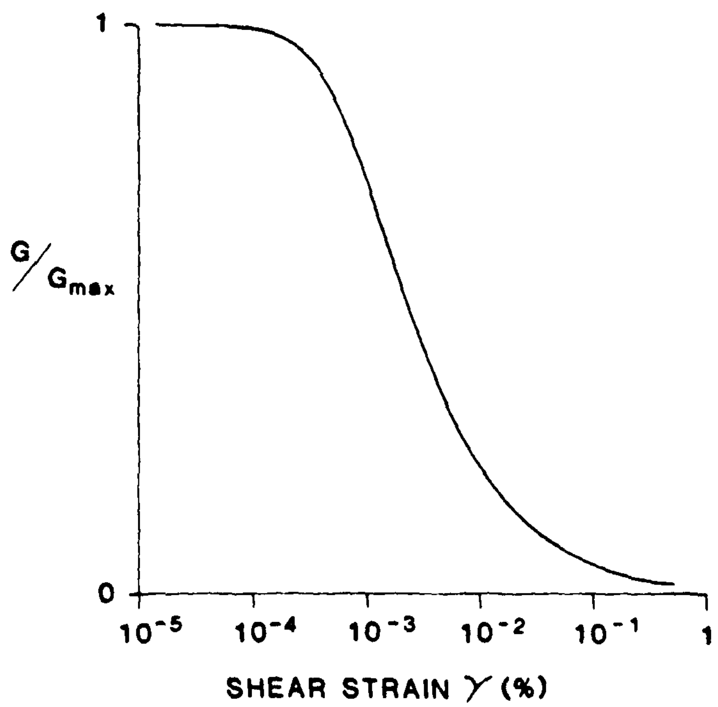

b)

Figure 7. (a) Form of the stress-strain curve for soils (b) Decrease in secant shear modulus with increasing strain.

$$\tau = \frac{\gamma}{\frac{1}{G_{max}} + \frac{\gamma}{\tau_{max}}} = \frac{\gamma G_{max}}{1 + \frac{\gamma}{\gamma_r}} \qquad (2)$$

where

G_{max} = maximum value of shear strain attained at low strain levels

γ_r = reference shearing strain = τ_{max}/G_{max}, where τ_{max} is the stress at which the material fails in shear

Hardin and Drnevich[10] gave the following formulae which enable τ_{max} and G_{max} to be computed from knowledge of certain material properties of the soil:

$$\tau_{max} = \left[\left(\frac{1 + K_o}{2} \sigma_v' \sin\Phi' + c'\cos\Phi'\right)^2 - \left(\frac{1 - K_o}{2} \sigma'_v\right)^2\right]^{1/2}$$

where

K_o = coefficient of lateral stress at rest,

σ_v' = vertical effective stress

c', Φ' = static strength parameters in terms of effective stress.

$$G_{max} = 14760 \times \frac{(2.973-e)^2}{1 + e} (OCR)^a (\sigma_m')^{1/2}$$

where:

e = void ratio

OCR = overconsolidation ratio

a = a parameter that depends on the plasticity index of the soil; the value of a can be obtained from the following table:

PI	a
0	0
20	0.18
40	0.30
60	0.41
80	0.48
≥100	0.50

σ_m' = mean principal effective stress in psf.

It is useful to characterize the stress-strain curve at any point such as A in Figure 7a by specifying the slope of the line joining A to the origin. The

slope of this line is known as the secant or equivalent shear modulus, in contrast to the tangent shear modulus, which is the slope of the tangent to the stress-strain curve at A.

Using Equations (1) and (2), we can write the following equation for the normalized secant shear modulus, G, as a function of normalized strain level.

$$\frac{G}{G_{max}} = \frac{1}{1 + \frac{\gamma}{\gamma_r}} \tag{3}$$

This curve has the shape shown in Figure 7b, in which the shear modulus has been normalized to its value at a strain level of 10^{-5}%.

In the non-linear range, soils exhibit hysteresis upon unloading, i.e. a residual strain is found upon reducing the stress to zero. This implies a loss of energy, or damping, under cyclic loading.

In order to describe the relationship between τ and γ during cyclic loading, an alternative formulation due to Ramberg and Osgood[11] is often used.

Upon loading $$\frac{\gamma}{\gamma_r} = \frac{\tau}{\tau_{max}} \left[1 + \alpha \left(\frac{\tau}{C_1 \tau_{max}} \right)^{R-1} \right]$$

where
α, R and C_1 are constants which permit adjustment of the shape and position of the curve.

For unloading from (τ_1, γ_1) the Ramberg-Osgood curve follows:

$$\frac{\gamma - \gamma_1}{\gamma_r} = \frac{\tau - \tau_1}{\tau_{max}} \left[1 + \alpha \left(\frac{\tau - \tau_1}{2C_1 \tau_{max}} \right)^{R-1} \right]$$

Figure 8a displays two hysteresis loops, computed using the Ramberg-Osgood with relations $\alpha = 1$, $C_1 = 4$, and $R = 3$, for cyclic loading at two different stress levels. It can be seen that, as the applied stress increases, the area under the hysteresis loop also increases. This implies an increase in damping with stress level. To quantify damping, we define the

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11. Ramberg, W., and Osgood, W.R. (1943) Description of Stress-Strain Curves by Three Parameters, Technical note 902, National Advisory Committee on Aeronautics, Washington, D.C.

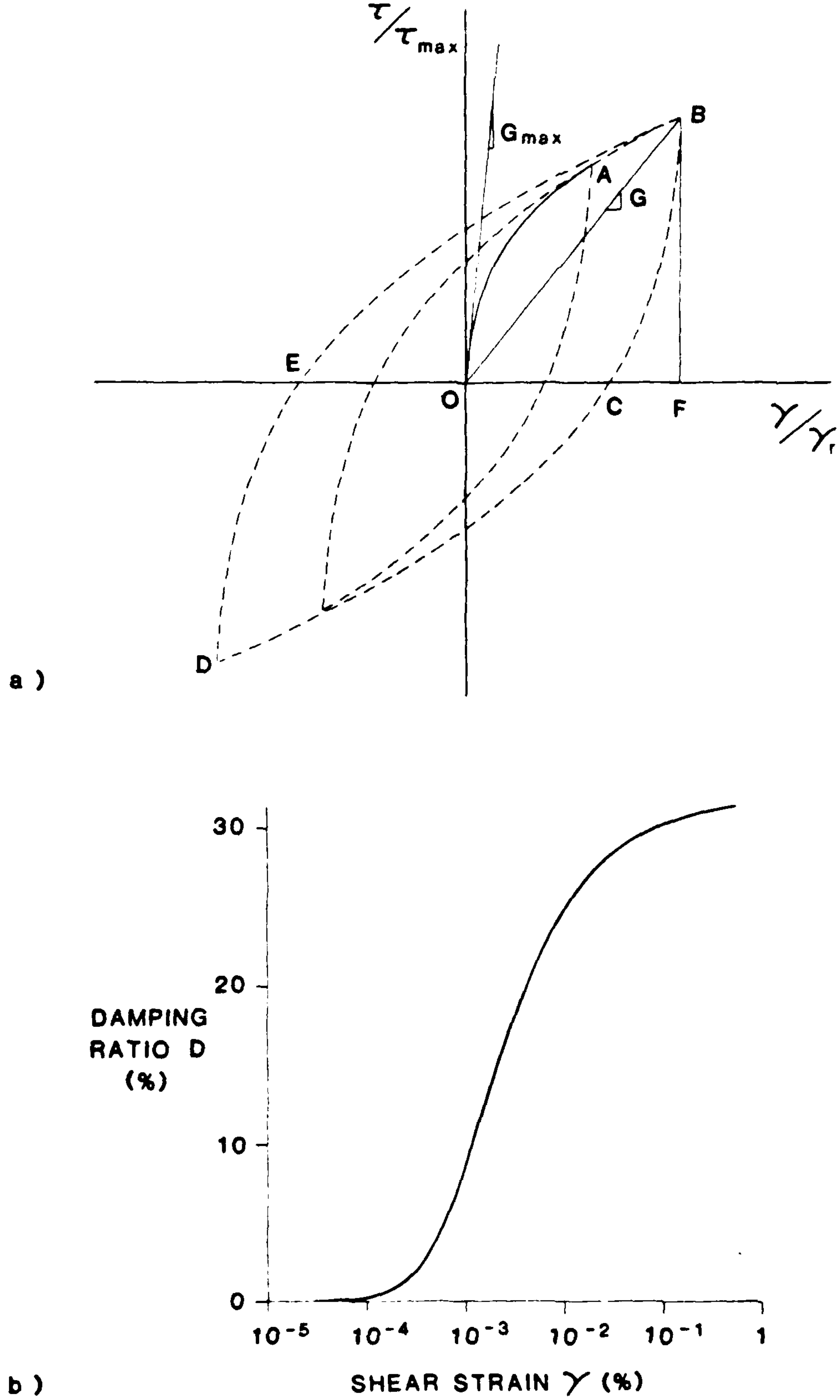

Figure 8. (a) Hysteresis loops for cyclic loading using Ramberg-Osgood[11] relations (b) Variation of damping ratio with strain level.

$$\text{Damping ratio, } D = \frac{1}{4\pi} \, \frac{\text{Area under hysteresis loop (BCDEB in Fig. 8a)}}{\text{Area of } \Delta \text{ OBF}}$$

The area of Δ OBF represents the strain energy in the sample at B assuming a linear stress-strain relation.

An example of the variation of damping ratio with strain level computed using this formulation is shown in Figure 8b.

Another approach to quantifying the stress-strain relation for soils was proposed by Seed and Idriss[12], who observed that laboratory measurements of equivalent shear modulus and damping versus strain level, if normalized by the values determined for a strain level of 10^{-6}, defined a narrow range of curves for different soil types. These empirical curves have been widely used in cases where detailed information on the dynamic properties of the soil column are otherwise lacking.

Figure 9 shows a comparison of representative curves for sands and cohesive soils determined by Seed and Idriss[12] and Hardin and Drnevich[10]. Also shown is the Ramberg-Osgood curve for six cohesive soils determined by Anderson and Richart[13]. It can be seen that for both soil types, the Seed and Idriss curve falls beneath the Hardin and Drnevich curve, but both sets of curves indicate that the reduction in shear modulus for cohesive soils occurs at lower strain levels than for cohesionless soils.

In summary, soils exhibit non-linear behavior at strain levels in excess of about 10^{-6}. In order to correctly predict the response of a particular soil column under earthquake loading, it is therefore essential to determine the dynamic properties of the soil underlying the site as a function of strain level. In addition, other factors, such as number of cycles of loading and effective stress, also affect the response and should be considered in any program to determine the dynamic properties of the soil column.

We now turn to a discussion of different methods for accomplishing this goal.

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12. Seed, H.B. and Idriss, I.M. (1970) Soil Moduli and Damping Factors for Dynamic Response Analysis, University of California at Berkeley, Earthquake Engineering Research Center, Report No. 70-10.

13. Anderson, D.G. and Richart, F.E. (1976) Effects of straining on shear modulus of clays, J. Am. Soc. Civ. Engrs., Geotech. Engrng. Div., 100 (No. GT12):1316-1320.

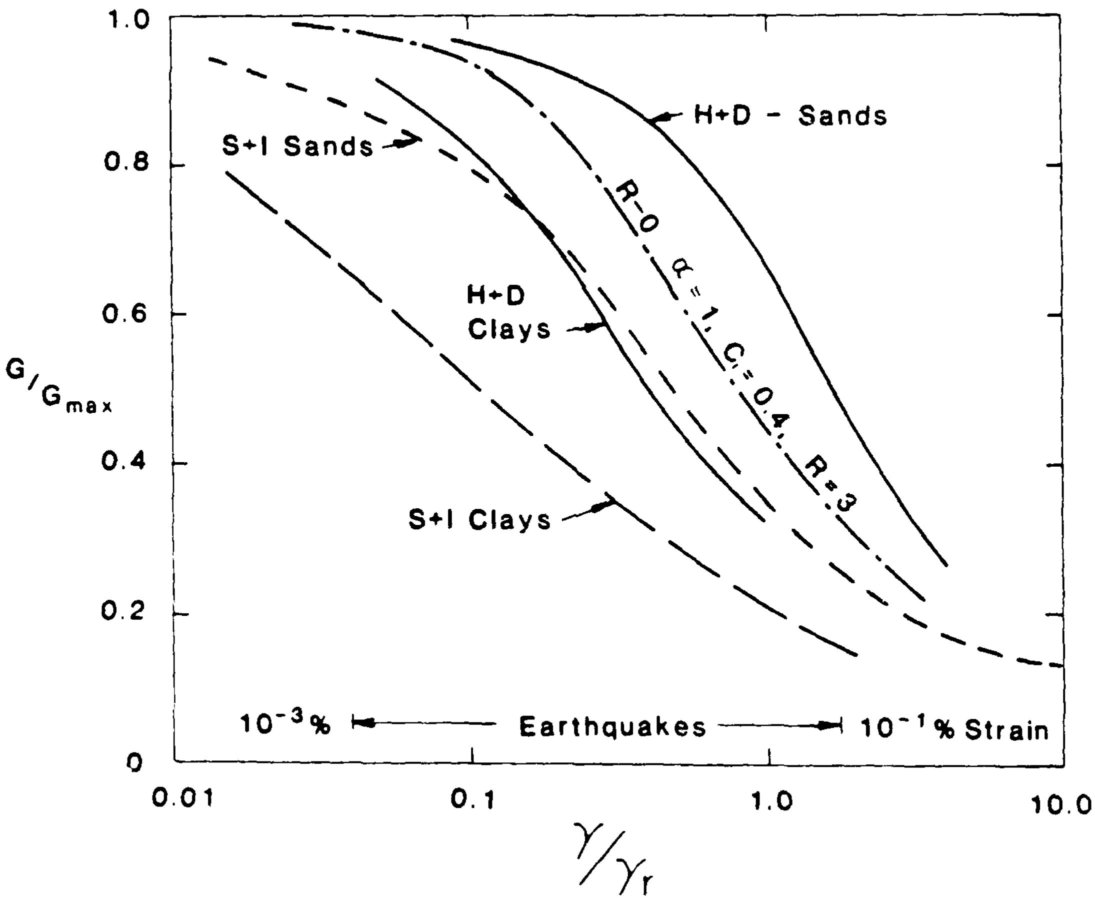

Figure 9. Comparison of representative curves for clays and sands determined using different methods.

3. LABORATORY METHODS

The use of laboratory techniques to measure the dynamic properties of soils has played a major role in developing our current understanding of the behavior of soils under dynamic loading conditions. The procedure involves removal of samples of soil from drilled boreholes and testing these samples in different types of laboratory apparatus. It is not the intention here to describe these laboratory techniques in detail. Comprehensive reviews on this topic can be found in Ladd et al[14], Woods[15], Yoshimi et al[9], and Silver[16]. Rather, this section will focus on general principles of the techniques and various problems that may reduce their usefulness for site response studies.

Cyclic triaxial and cyclic simple shear methods involve subjecting a soil sample to a constant hydrostatic pressure and then measuring its deformation under a cyclically-applied axial or shearing stress, respectively. The objective of these tests is to reproduce in the laboratory conditions similar to those that may be experienced by the soil specimens in situ during earthquake loading. From analysis of the deformation of the sample at a given stress level, it is possible to compute the shear modulus or the Young's modulus, as well as material damping, for the specimen. Figure 10 shows the range of shear strains which are typically encountered in cyclic laboratory tests. Because of difficulties in measuring extremely small amounts of deformation, the effective lower limit of shearing strain achievable in these tests is about 10^{-4}. Smaller strains are possible if the specimen is deformed via a torsional stress, either in a cyclic loading mode or in a uni-directional mode.

A different approach to determining modulus and damping characteristics of soils is the resonant column test, which is based on the theory of wave

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14. Ladd, C.C., Foott, R., Ishihara, K., Schlosser, F., and Poulos, H.G. (1077) Soil dynamics and its application to foundation engineering, Proc. 9th Intl. Conf. on Soil Mechanics and Foundation Engineering, Tokyo:421-494.

15. Woods, R.D. (1978) Measurement of dynamic soil properties, Proc. Am. Soc. Civ. Engrs. Spec. Conf. on Earthquake Engineering and Soil Dynamics, Pasadena, Calif.:91-178.

16. Silver, M.L. (1981) Load, deformation and strength behavior of soils under dynamic loadings, Proc. Intl. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri, at Rolla:873-895.

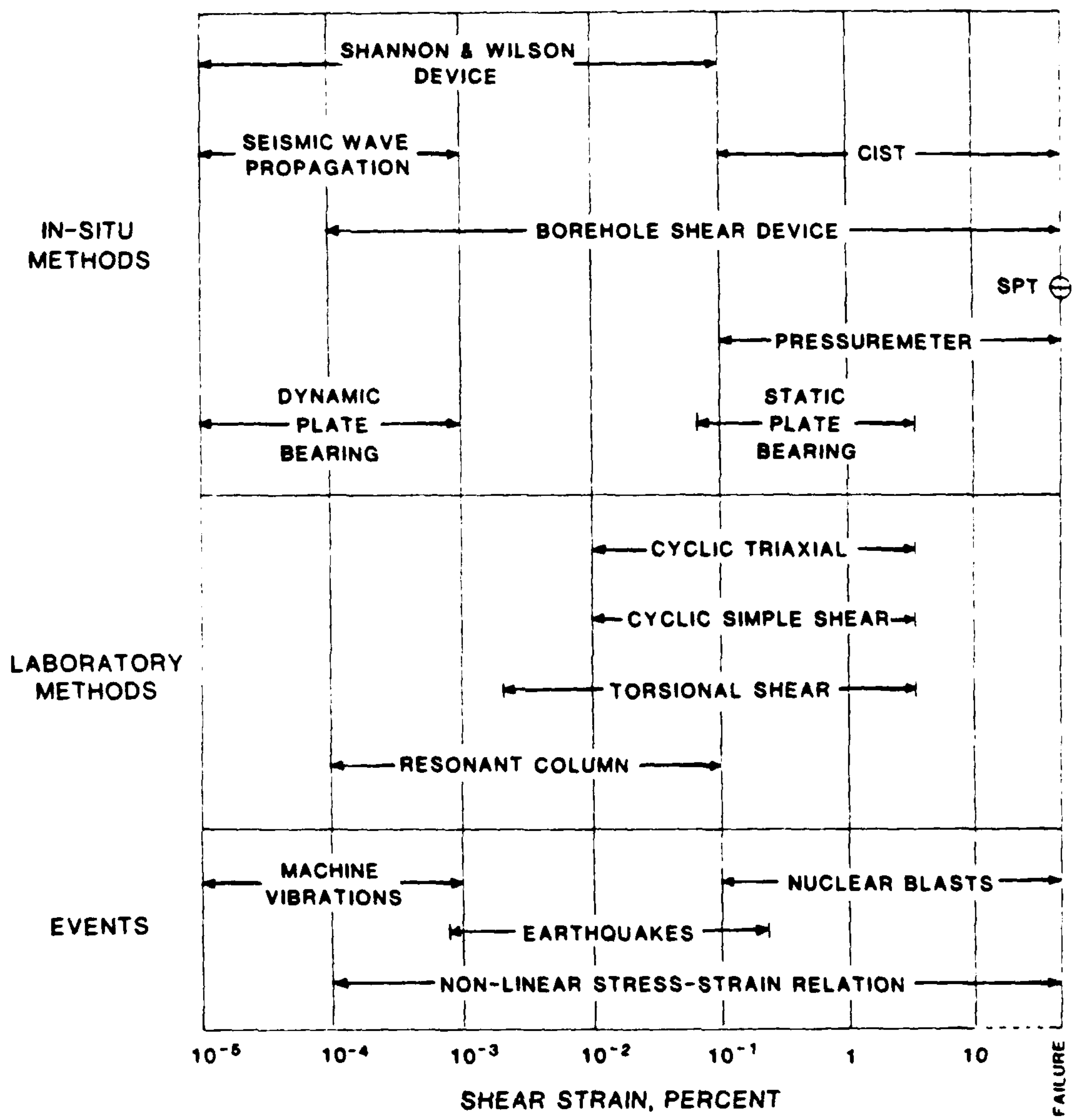

Figure 10. Approximate shearing strain ranges of field and laboratory measurement methods and events of interest (modified from Fugro[8]).

propagation in prismatic rods (Richart et al[7], Chapter 3). In a resonant column apparatus a cylindrical soil specimen is cyclically deformed at constant frequency under either axial or torsional loading conditions, and the exciting frequency adjusted until the specimen experiences resonance. The modulus is computed from the resonant frequency and the geometric properties of the specimen and driving apparatus. Under axial loading, values of Young's modulus are obtained, whereas under torsional loading, values of shear modulus are given. With this apparatus a wide range of strain levels can be achieved. It is also possible to determine damping by turning off the driving power at resonance and recording the vibrations as they decay.

The advantages of laboratory testing methods include the ability to achieve large strains, to impose known boundary conditions, and to vary the frequency and duration of loading. Also, additional parameters, such as variations in pore pressure, can be monitored.

Opposing these advantages, however, are several disadvantages that reduce the usefulness of laboratory measurement techniques for site response studies. For example, because stresses are mechanically applied to the edges of the specimens, large variations in stress and strain can occur within the samples. This problem can, however, be overcome in the torsional shear and resonant column methods by using hollow cylindrical samples.

The most severe problem with using laboratory data to infer in situ soil properties is that, during collection, the soil sample is invariably disturbed to some degree. This disturbance involves changes in pore water pressure, soil density and the arrangement of soil particles. In addition, during removal of the sample from the soil, the in situ state of stress is released. As a result, laboratory measurements of shear modulus fall systematically below values determined for the same soil column in situ at the same strain level. Figure 11 compares values of shear modulus as a function of shear strain determined using laboratory techniques[17] with values derived using different field techniques[12,17,18]. It can be seen that differences of up to 500 % exist between the laboratory-determined values and the field-determined values.

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17. Shannon and Wilson, Inc. (1967) Personal communication reported in Seed and Idriss[12].

18. Tsai, N.C., and Housner, G.W. (1970) Calculation of surface motions of a layered half-space, Bull. Seis. Soc. Am. 60(No. 5):1625-1652

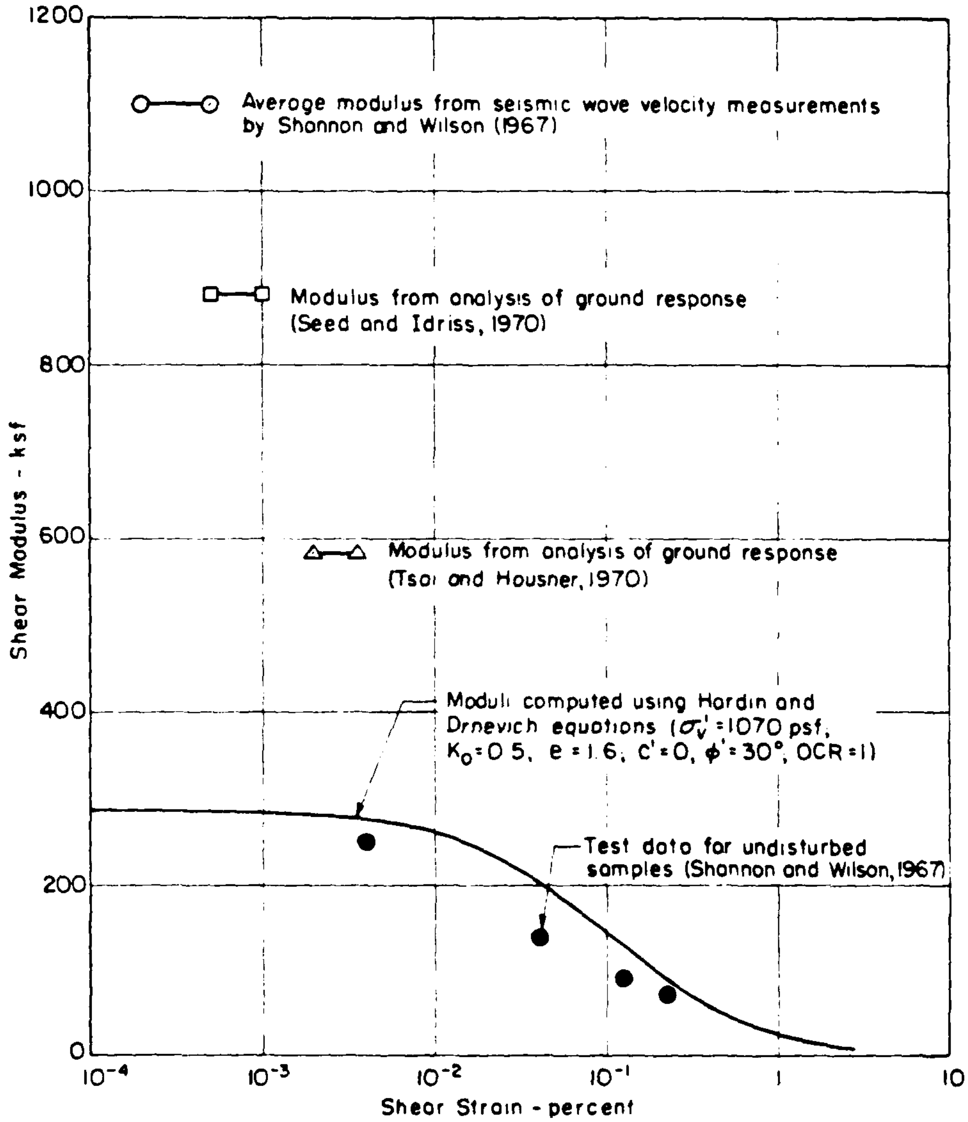

Figure 11. Shear modulus determinations for Union Bay clay at depth of about 80 ft (Seed and Idriss[12]).

Anderson and Woods[19] have demonstrated that there is an important time effect which should be taken into account in laboratory testing. They show that if laboratory samples are maintained under a constant confining pressure, the shear modulus increases linearly with the logarithm of time. If the laboratory determined values are extrapolated to the age of the soil deposit using this logarithmic relation, much better agreement between the laboratory and in situ values at low strains is obtained (Figure 12). It is, however, important to note that application of the same procedure to modify laboratory-determined values of shear modulus at high strain levels has not been demonstrated.

Other uncertainties related to the interpretation of laboratory measurements are presented by Saada et al[20], who discuss the influence of different boundary conditions on the results obtained in the laboratory soils tests; by Silver and Park[21], who evaluate the use of stage testing techniques; and Horn[22], who found that the shear strength of a soil sample determined in a laboratory test was sensitive to the size of the soil sample used.

4. IN SITU TECHNIQUES

4.1 Introduction

It is apparent from the discussion in the previous section that laboratory tests for dynamic moduli, while providing information on soil properties over a

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19. Anderson, D.G. and Woods, R.D. (1975) Comparison of field and laboratory shear moduli, Proc. Am. Soc. Civ. Engrs. Conf. on In Situ Measurement of Soil Properties, Raleigh, North Carolina 1:69-92.

20. Saada, A.S., Fries, G., and Ker, C.-C. (1983) An evaluation of laboratory testing techniques in soil mechanics, Soils and Foundations, Japanese Soc. Soils Mech. and Found. Engrng. 23(No. 2):98-112.

21. Silver, M.L., and Park, T.K. (1975) Testing procedure effects on dynamic soil behavior, J. Am. Soc. Civ. Engrs., Geotech. Engrng. Div., 101(No. GT10):1061-1083.

22. Horn, H.M. (1979) North American experience in sampling and laboratory dynamic testing, Geotech. Testin J. 2(No. 2):84-97.

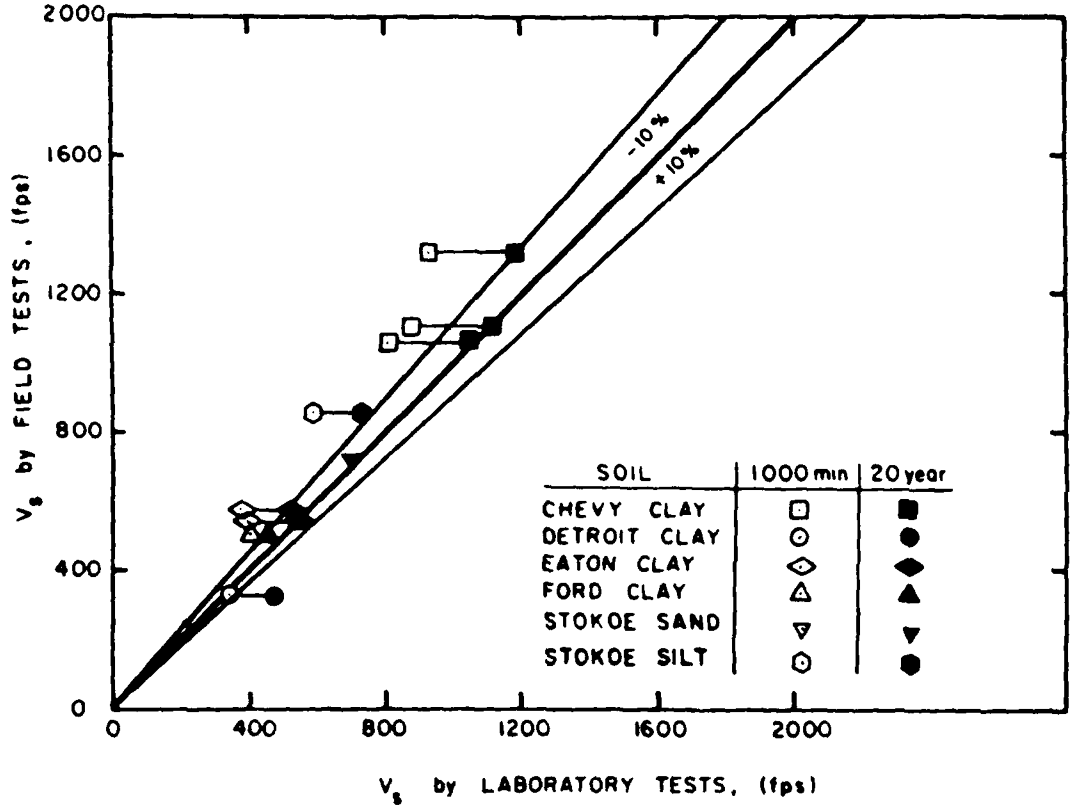

Figure 12. Adjustment of laboratory results for time effect (Anderson and Woods[19]).

range of loading paths and parameter variations, may not truly reflect the in situ properties of soils because of uncertainties related to sample preparation, effective states of stress and data interpretation.

One way to reduce the uncertainty associated with using empirical results is to directly measure the elastic and inelastic moduli of soils in situ under different loading conditions. We now review some of the methods by which this can be accomplished.

The goal of any successful field measurement program to estimate site response should be to derive dynamic soil properties under conditions similar to those which might be experienced during earthquake- or blast-induced loading. Ideally, this program should include measurements:

- of modulus and damping made over the strain levels of interest (10^{-6} to 10^{-3} for earthquakes; 10^{-5} to failure for nuclear explosions)
- at various overburden levels
- under cyclic loading at appropriate frequencies
- under volumetric and shearing modes of deformation
- at different fluid saturation levels, with monitoring of associated phenomena, such as pore pressure variations.

Different in situ techniques have been used or proposed to address various elements of these objectives, but no one existing technique addresses all of them. The objective of this section is to present a review of the various strengths and weaknesses of some of the methods that have been proposed, in order to provide a basis for a workable field program that will provide the necessary information for site response studies.

Three classes of in situ techniques are considered:

(1) Seismic Wave Propagation Methods
(2) Dynamic Loading Methods
(3) Static Loading Methods

4.2 Seismic Wave Propagation Methods

Seismic wave propagation methods involve monitoring the passage of a stress wave at various points in the soil column following the introduction of energy,

such as a sudden impact, at another point. At low strain levels (less than 10^{-6} strain), the stress- strain relation for most soils is linear. As a result, at low strains the energy travels in the form of two waves with different speeds; a faster P wave, which propagates by compressional motion of the ground, and a slower S wave, which travels by shearing motion. S waves are further divided into SV and SH phases, which travel at the same speed but involve vertical and horizontal polarizations, respectively. Near the surface of the earth, additional surface waves are possible, consisting of Rayleigh waves, which are vertically polarized, and Love waves, which are horizontally polarized. At the boundary between two soil layers with different properties, additional boundary waves are possible, but these waves die off quickly with distance from the boundary, and are not normally considered in dynamic soil analyses.

As stress waves propagate outwards from the initial source of energy, their intensity diminishes because the energy must be distributed over an increasingly greater area of the wave front. If soils were perfectly elastic at all strain levels, then this geometrical attenuation would be the only factor causing a dropoff in intensity with distance. However, the hysteretic nature of the stress-strain relation for soils under cyclic loading (Figure 8a) means that additional damping occurs during each loading cycle.

Using elastic theory, we have the following relations between the velocities of P and S waves, V_P and V_S respectively; density, ρ; and the shear modulus, G, the bulk modulus, K, Young's modulus, E, and Poisson's Ratio, ν.

$$G = \rho V_S{}^2$$

$$K = \rho(V_P{}^2 - 4/3\ V_S{}^2)$$

$$E = \rho V_S{}^2\ [2(1+\nu)]$$

$$2\nu = \frac{V_P{}^2/V_S{}^2 - 2}{V_P{}^2/V_S{}^2 - 1}$$

Measurements of V_P, V_S and ρ for a soil mass therefore allows the elastic moduli to be determined.

As the strain level increases, the stress-strain relation for soils becomes non-linear (Figure 7a), and the strict mathematical distinction between P and S waves is lost. However, compressional and shear waves can often still be detected and their velocities used in the above expressions to define equivalent elastic moduli, which correspond to taking the secant of the stress-strain relation in Figure 7a. However, moduli determined in this manner give no indication of the shape of the stress-strain hysteresis loop. The material damping characteristics of the soil must therefore be obtained by other methods.

A report by Fugro[8] for the Electric Power Research Institute (EPRI) provides a discussion of waveform-fitting techniques from which the hysteretic stress-strain curve for different constitutive models of soil can be determined at different strain levels. Although more complicated to implement than using seismic wave velocities, these methods allow a more accurate determination of soil properties, including damping.

Seismic wave propagation techniques for determining dynamic soil properties can be separated into three types depending upon the relative position of sources and receivers relative to the surface:

- Surface methods
- Cross-Hole Methods
- Down-Hole Methods

4.2.1 Surface Methods

Surface techniques involve the source and receiver at or near the surface. These methods are therefore relatively inexpensive and quick to carry out. The surface techniques of seismic reflection and refraction (Dobrin[23]) are often useful for reconnaissance investigation at a site to determine the depths and elastic wave velocities of different layers within the soil column.

The use of surface (generally Rayleigh) waves, generated either by a vibration or impact source, is another useful technique which provides information on V_S as a function of depth (for example see Ballard and

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23. Dobrin, M.B. (1976) Introduction to Geophysical Prospecting, 3rd Edition, McGraw-Hill, New York.

McLean[24]). Nazarian and Stokoe[25] present a spectral analysis technique for surface wave analysis which eliminates some of the problems with older interpretation techniques.

The main drawback with using these surface methods for dynamic soils analysis is that the propagation paths are long and therefore the measurements generally only provide low strain estimates of moduli at depth.

4.2.2 Cross-Hole Methods

In the cross-hole method the source and t e receiver are placed in separate boreholes. Using receiver holes at different distances from the source eliminates problems with source timing and leads to more precise determination of seismic wave velocities. The expense of drilling the boreholes and instrumenting the holes adds considerably to the cost of this type of survey, but in compensation, moduli values can be determined at different depths in the soil column. Consequently, the cross-hole technique has been widely used in dynamic site investigations.

Figure 13a shows a field setup for cross-hole studies using three receiver holes (Hoar and Stokoe[26]). Figure 13b provides examples of the field records obtained. A vertical impulse was applied at the source. The S wave arrival on the records is therefore larger in amplitude than the P wave arrival. This is useful, since the S wave arrival time can be easily picked. Also shown in Figure 13b is the output from a vertical velocity transducer mounted on the impulse rod showing the origin time of the source signal.

Shannon and Wilson, Inc., in cooperation with Agbabian Associates, developed an in situ impulse device which uses the cross-hole concept and which

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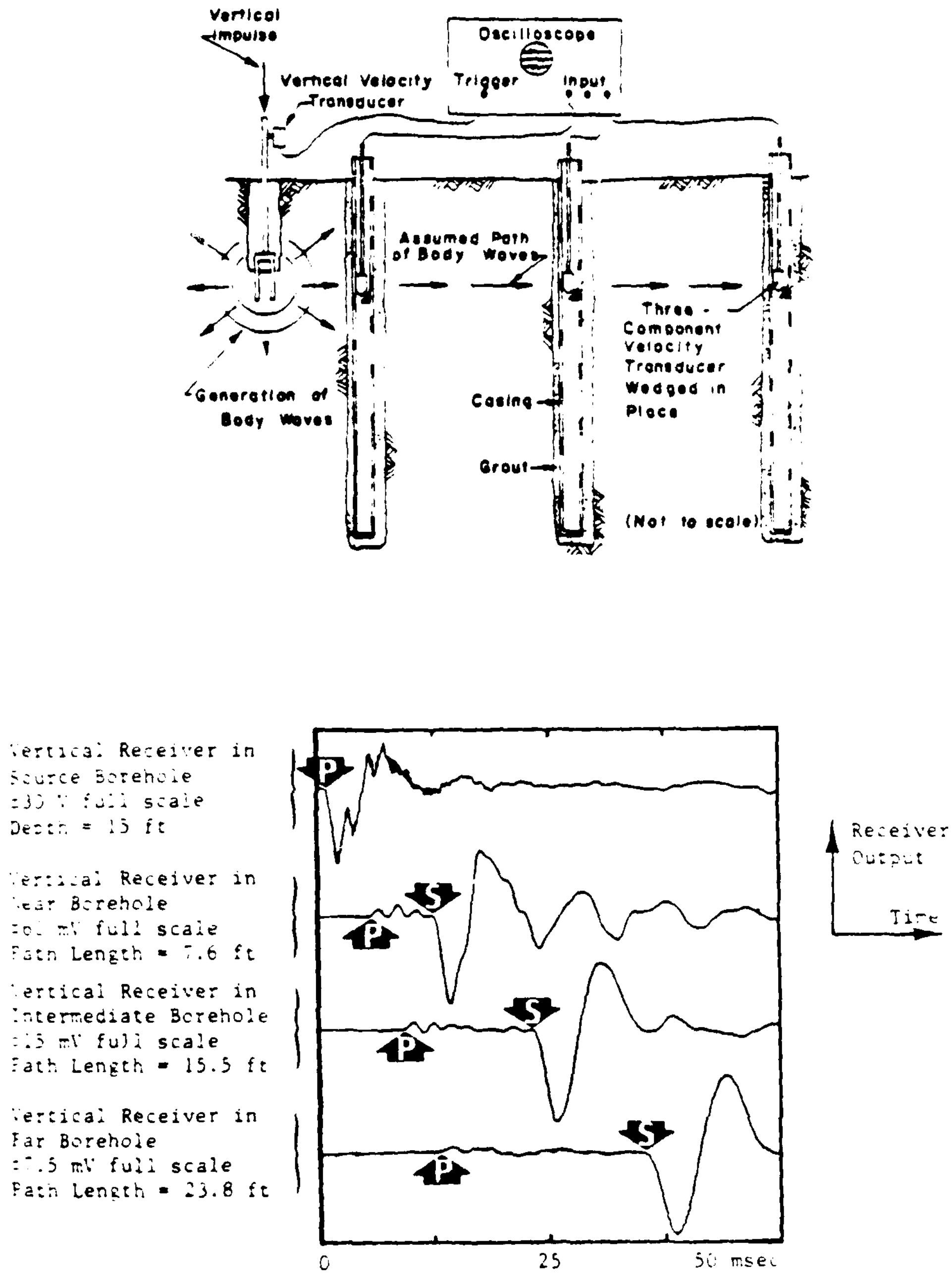
24. Ballard, R.F., and McLean, F.G. (1975) Seismic field methods for in situ moduli, Proc. Am. Soc. Civ. Engrs. Conf. on In Situ Measurement of Soil Properties, Raleigh, North Carolina 1:121-150.

25. Nazarian, S., and Stokoe, K.H. (1984) In situ shear wave velocities from spectral analysis of surface waves, Proc. 8th World Conf. Earthqu. Engrng., San Francisco, Calif. 3:31-38.

26. Hoar, R.J., and Stokoe, K.H. (1984) Field and laboratory measurements of material damping of soil in shear, Proc. 8th World Conf. Earthqu. Engrng., San Francisco, Calif. 3:47-54.



a)

b)

Figure 13. (a) Cross-sectional view of cross-hole seismic method (b) Typical waveforms for shear waves (Hoar and Stokoe[26]).

is capable of generating strain levels as large as 10^{-3} (Miller et al[27]; SW-AA[28]). Figure 14 shows a schematic representation of this in situ impulse device.

The system consists of a hole-locking mechanical apparatus and a drop hammer. Once the apparatus has been locked against the borehole wall at a depth of interest, a hammer is dropped from a predetermined height onto the locked mechanism. The energy imparted by falling mass is transferred into the soil. The weight falls on the coupling mechanism such that most of the energy is shearing action, and thus a strong shear wave is created.

The induced wave is detected at points located at different radial distances from the source. Distances are typically of the order of 4, 8 and 16 feet. Horizontal and vertical velocity sensitive geophones are used to monitor soil response. These transducers are pushed against the borehole wall with a pneumatic expander. Because receiving holes are located close to the source, it is essential in this method that each boring be surveyed to establish deviations from verticality. Shear moduli and shearing strain amplitudes are evaluated by utilizing equivalent elastic theory while assuming plane-wave propagation. The impulse test method has been successfully employed at depths of up to 200 feet. Plots of secant shear modulus versus shearing strain derived from impulse tests using this device are shown in Figure 15.

A high energy cross-hole device utilyzing vibratory motion was also proposed by Shannon and Wilson (Miller and Brown[29]), but, because of coupling problems in the borehole, was never made operational. A low-strain cross-hole vibratory technique was successfully tested by Bodare and

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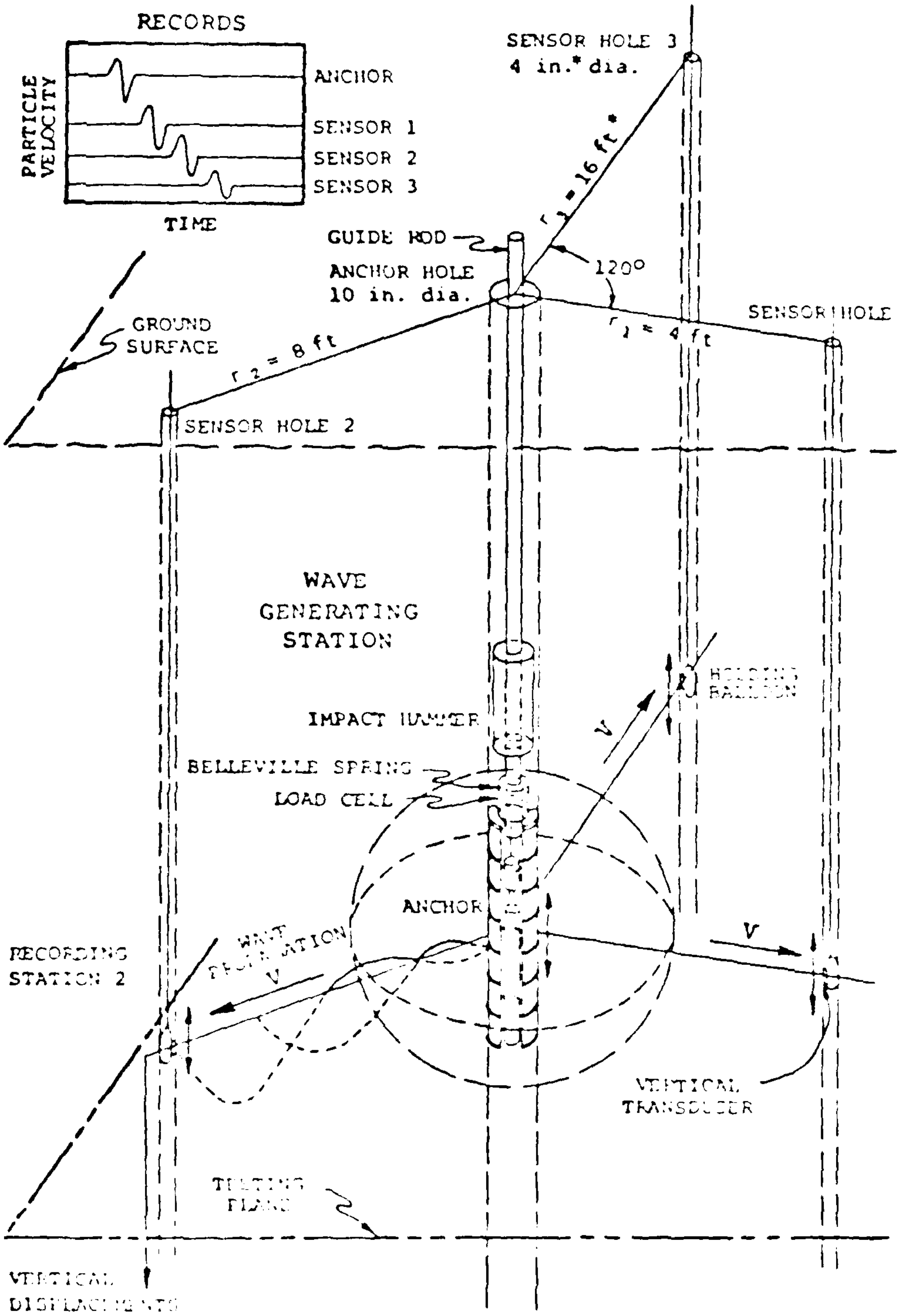
27. Miller, R.P., Troncoso, J.H. and Brown, F.R. (1975) In situ impulse test for dynamic shear modulus of soils, Proc. Am. Soc. Civ. Engrs. Conf. on In Situ Measurement of Soil Properties, Raleigh, North Carolina 1:319-335.

28. Shannon & Wilson, Inc., and Agbabian Associates (1976) In Situ Impulse Test: An Experimental and Analytical Evaluation of Data Interpretation Procedures, Technical Report No. NUREG 0028, NRC-6, prepared for U.S. Nuclear Regulatory Commission.

29. Miller, R.P., and Brown, F.R. (1972) Shear modulus determination of soils by in situ methods for earthquake engineering, Proc. Intl. Conf. on Microzonation, Seattle, Washington 2:545-558.



*(1 FT = 0.305m, 1 IN = 2.54cm)

Figure 14. Schematic representation of in situ impulse test (SW-AA[2*]).

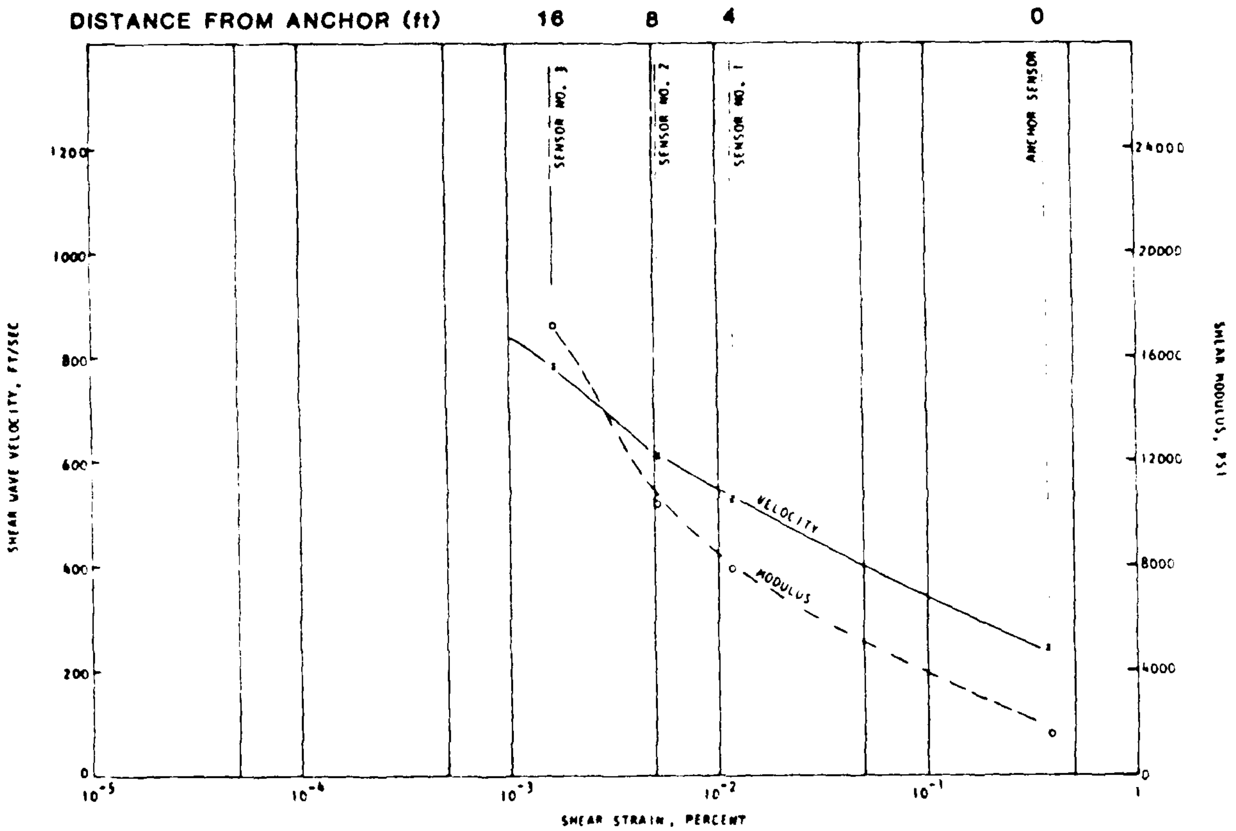


Figure 15. Example of modulus and velocity values versus strain level obtained in the in situ impulse test (SW-AA[28]).

Massarsch[30]. Another possible cross-hole source is a dynamic screwplate device (Andreasson[31]), from which both impulsive and vibratory signals can be produced. Hoar and Stokoe[26] reported the results of cross-hole techniques in which values of material damping were determined by analysis of wave amplitudes and also by Fourier analysis of the records.

In discussing cross-hole techniques, we also need to mention ultra-high-strain soil failure tests (strains from 10^{-3} to 10^{1}) associated with misile silo emplacement, such as the Cylindrical In Situ Test (CIST). In these tests high explosive primer cord is placed in a cylindrical container and detonated at essentially one instant of time, thereby generating a very large stress wave in the soil. This stress wave initially propagates outward as a high amplitude shock wave. These tests, which are intended to reproduce conditions during high-energy nuclear blasts, are very expensive to perform and would not normally play a part in any routine soils investigation program. However, the same techniques that are used to analyze the data in CIST experiments, such as waveform analysis, would also be applicable to analysis of cross-hole measurements in the high strain region.

4.2.3 Down-Hole Methods

In the down-hole method only one borehole is used. The source is normally located at the surface and a series of receivers are placed down the borehole. This procedure is less expensive to perform than cross-hole methods yet provides some information about soil properties at depth. For example, by measuring the time of arrival of the compressional P wave at various depths down a borehole, extremely accurate estimates of the compressional wave velocity as a function of depth can be obtained. When the whole of the recorded trace is used, the down-hole technique is known as Vertical Seismic Profiling (VSP). Figure 16

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30. Bodare, A., and Massarsch, K.R. (1984) Determination of shear wave velocity by different methods, Proc. 8th World Conf. Earthqu. Engrng., San Francisco, Calif. 3:39-46.

31. Andreasson, B.A. (1981) Dynamic deformation characteristics of a soft clay, Proc. Intl. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri, at Rolla: 65-70

shows an example of VSP data obtained by Keho et al[32], using an inclined weight-drop impact source. These data were recorded using a three-component velocity transducer clamped at different depths down a borehole. With three-component data, processing techniques can be used to selectively enhance different types of waves. Figure 16 displays the vertical component of motion, showing a strong P wave arrival, large Rayleigh waves and a weak SV arrival. Notice the large amplitude of the Rayleigh waves at the surface. In the near surface regime, fairly high strains are therefore generated by this technique.

A particular variation of the VSP technique is known as hydraulic VSP, in which hydrophones replace clamped detectors down the borehole. This particular application of the VSP technique, developed jointly by Weston Geophysical Corporation and the Earth Resources Laboratory at the Massachusetts Institute of Technology, has been successfully used to estimate the continuity and hydraulic conductivity of fractures in rock as determined from analysis of tube waves (Levine et al[33]).

Tube waves are high amplitude borehole waves that are generated by the squeezing of fractures during passage of a compressional wave from the source. If the fractures contain water, some of the water is squeezed into the borehole, generating the tube waves. Figure 17 illustrates a typical field set-up and shows a field record on which two tube waves generated at different depths can be seen. The precise depth at which the fractures intersect the borehole can be identified from the depth at which the upgoing and downgoing tube wave arrivals coincide with the direct P wave arrival. From a comparison of the relative amplitude of the tube wave with the generating P wave at the fracture, the hydraulic conductivity of the fracture can also be estimated (Levine et al[33]).

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32. Keho, T.H., Toksöz, M.N., Cheng, C.H. and Turpening, R.M. (1984) Wave dynamics in a Gulf Coast VSP, in Vertical Seismic Profiling, Part B: Advanced Concepts, M.N.Toksöz and D.H.Johnston, Eds., Geophysical Press, London:205-235.

33. Levine, E.N., Cybriwsky, Z.A. and Toksöz, M.N. (1984) Detection of permeable rock fractures and estimation of hydraulic conductivity by 3-D vertical seismic profiling, in Proc. NNWA/EPA Conf. on Surface and Borehole Geophysical Methods in Ground Water Investigations, D.M.Nielsen, Ed., San Antonio, Texas:853-876.

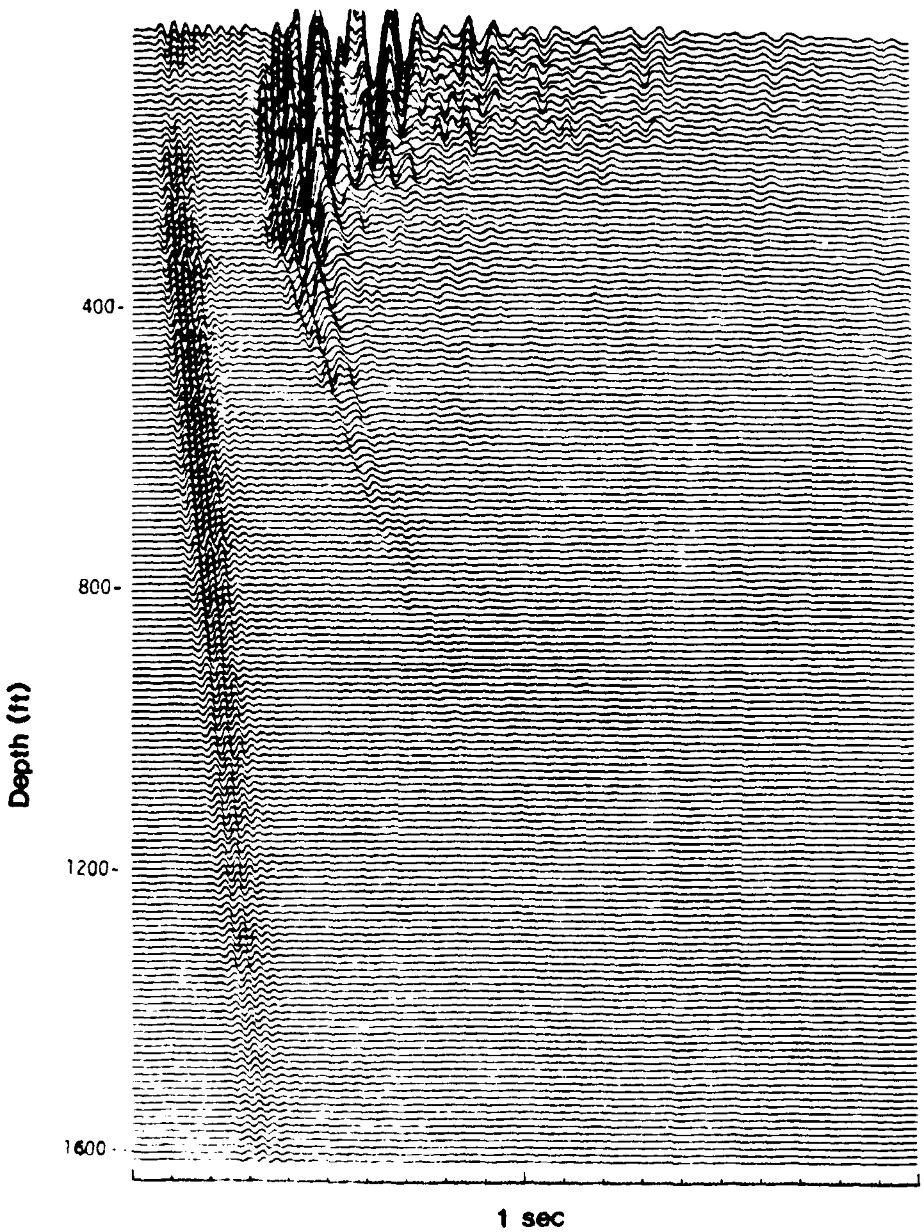

Figure 16. Vertical component of processed VSP data (Keho et al[32]).

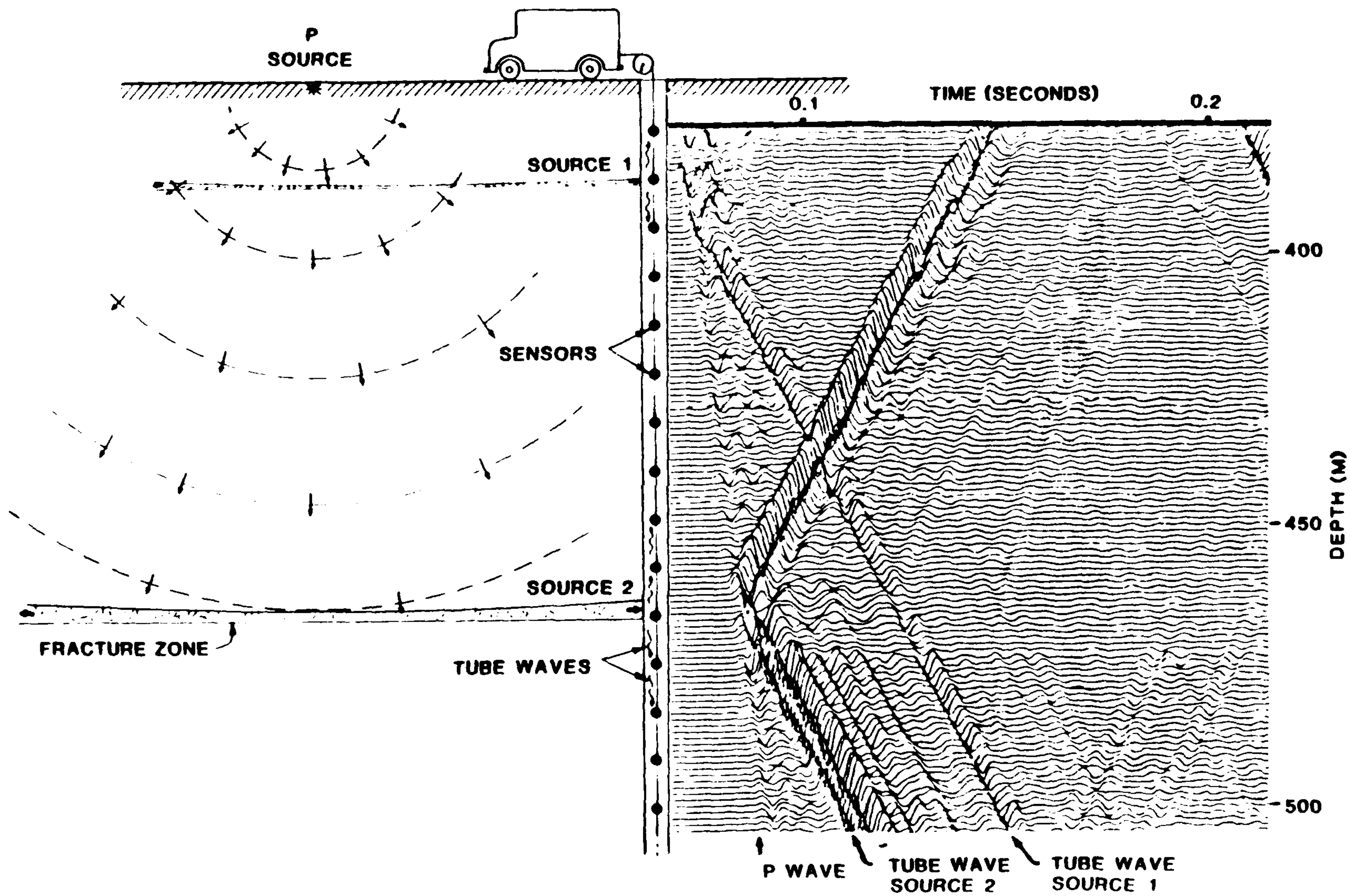

Figure 17. Hydraulic VSP survey (Levine et al[33]).

A possibility exists that, in the case of soils, water will be preferentially injected from the more permeable layers in the soil column, leading to a continuum of tube waves. By analysis of these tube waves, it may be possible to estimate the relative permeability of the different soil layers.

4.3 Dynamic Loading Methods

Dynamic loading methods form the second general class of in situ test methods. These tests are characterized by the concept that all measurements are made on the excitation system, and soil properties are determined from the response of the soil/loading system. Since the measurements are made at the excitation source, soils properties determined using dynamic loading methods generally correspond to higher strain levels than seismic wave propagation methods. However, with dynamic loading methods, soil properties are only measured in the immediate vicinity of the loading device.

Dynamic response techniques can be classified into two types: surface and subsurface. Surface methods include analysis of the response of model footings or foundations to transient or steady-state loads. An example of a subsurface dynamic response technique is the vibratory screwplate device described by Andreasson[31].

Holzlohner[34] reported the results of steady-state testing methods that were performed using a rotating mass exciter applied to force plates of different sizes. The frequency of the exciting mechanism was adjusted until resonance was achieved. By analyzing the response of the plate at resonance using an equivalent elastic half-space method, values of shear modulus in the soil mass were derived. Figure 18a shows plots of shear modulus determined in this manner versus normalized dynamic stress at resonance. It can be seen that, as the dynamic stress at resonance approaches the static contact stress, the shear modulus decreases. Comparing the general trend of the curve in Figure 18a

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34. Holzlohner, U. (1967) The determination of dynamic properties of a vibrating soil-foundation system by small-scale tests, Proc. Intl. Symp. on Wave Propagation and Dynamic Properties of Earth Materials, New Mexico:631-640.

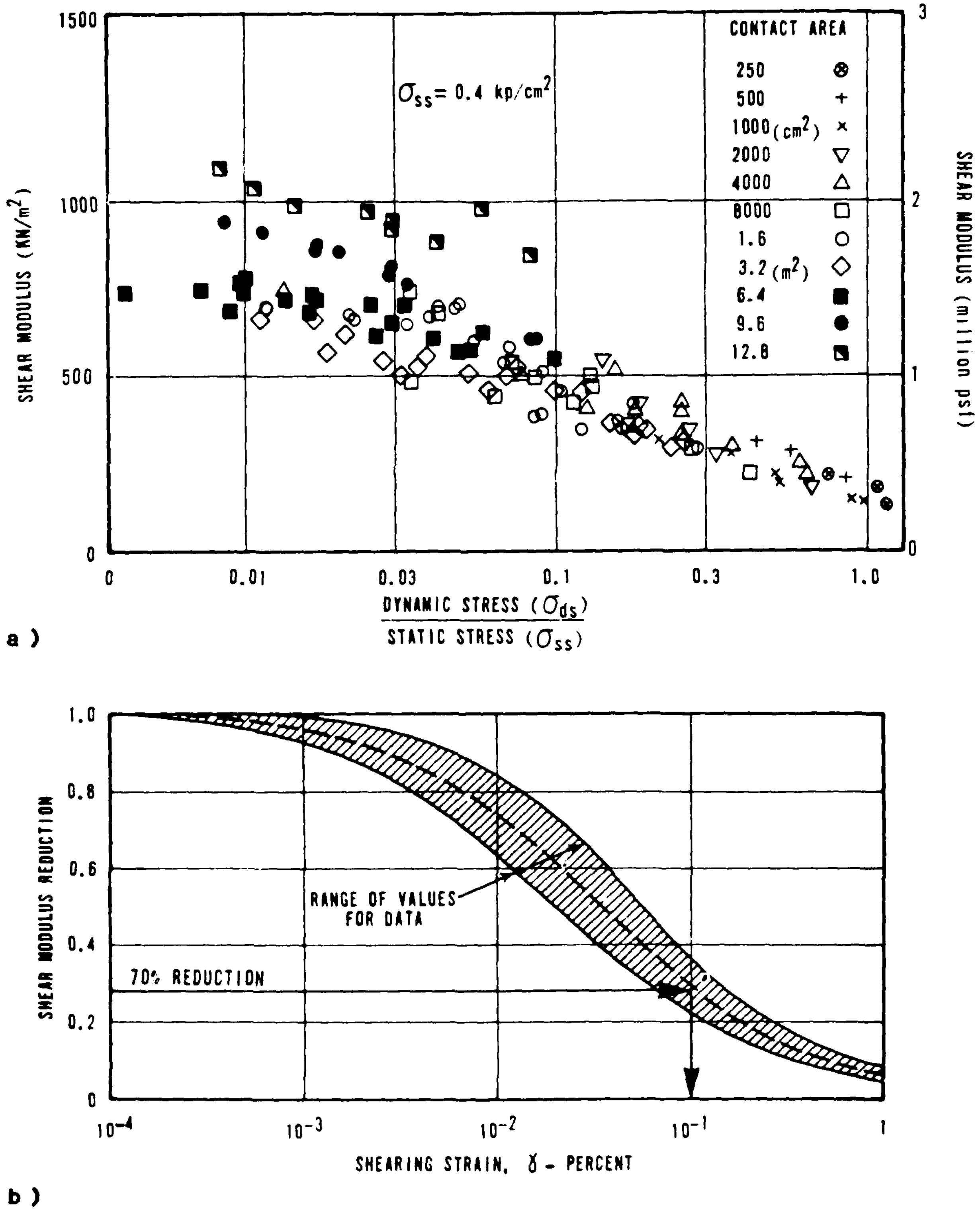

Figure 18. (a) Results of German steady-state tests reported by Holzlohner[34] (b) Seed and Idriss[12] modulus reduction curves (from Fugro[8]).

with the generalized Seed-Idriss relationship between shear modulus and shearing strain shown in Figure 18b, it appears that average shearing strains approaching 10^{-3} were obtained.

While not a dynamic response method in the engineering sense of the word, results reported by Abdel-Ghaffar and Scott[35] illustrate that strong ground motion records from earthquakes can also be used to determine dynamic soil properties. In this investigation Abdel-Ghaffar and Scott analyzed strong motion records from two California earthquakes as measured on the crest of an earth dam and on an adjacent rock abutment. Their results, expressed in terms of shear modulus and damping ratio variations with shear strain level, are shown in Figures 19a and 19b. Although there is a wide scatter in the data points, they do seem to indicate a decrease in shear modulus with increasing strain level and a corresponding increase in damping ratio, as observed in other tests.

An example of a subsurface dynamic response system is the Borehole Shear Device described by Sidey et al[36] and illustrated in Figure 20. The device consists of a self-boring tip which advances the measuring instrument to the required depth in the soil column. The instrument is coupled to the soil by radially expanding a number of axial shoes against the side of the borehole. This procedure reimposes the previous in situ state of stress. A harmonic rotation of increasing amplitude is then applied to the coupling mechanism; measurements of the torque and corresponding angular rotation serve to determine the stiffness characteristics of the soil. Based upon the results reported by Sidey et al[36], this device appears capable of generating shear strains in the soil ranging from 10^{-6} to failure. The report produced by Sidey et al[36] for the Air Force Weapons Laboratory, Kirtland Air Force Base, was a feasibility study of the borehole shear device. It is not known whether this system is presently operational.

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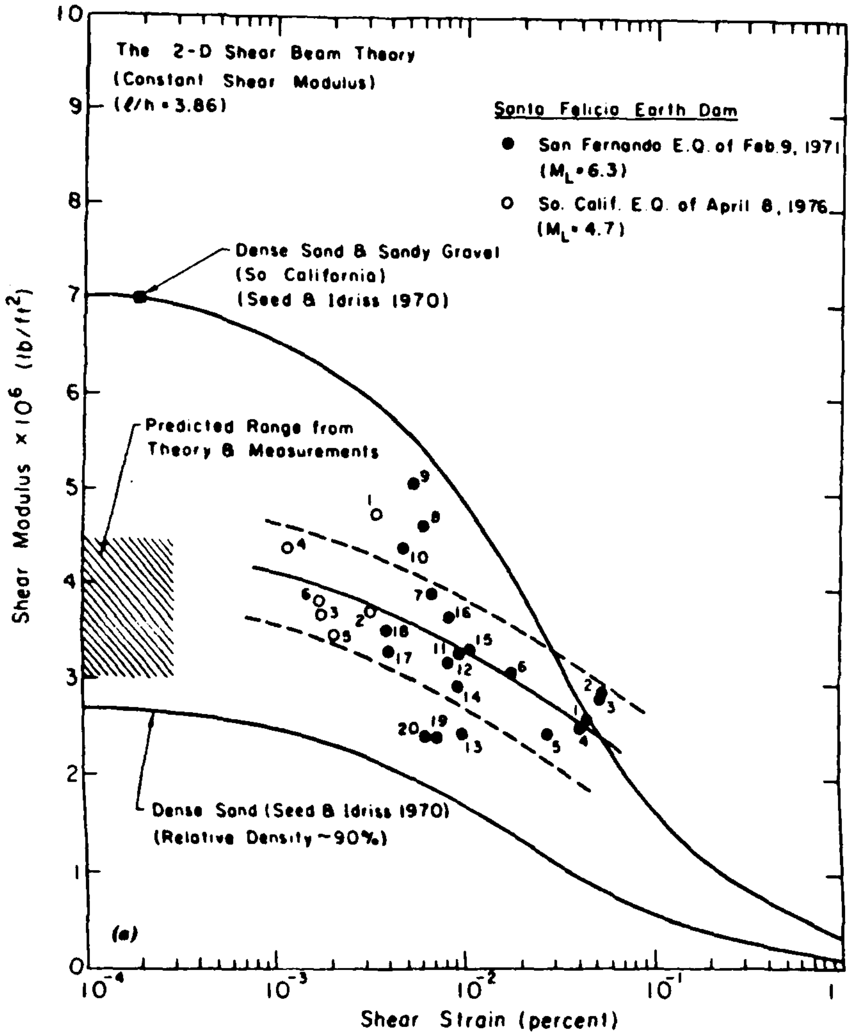
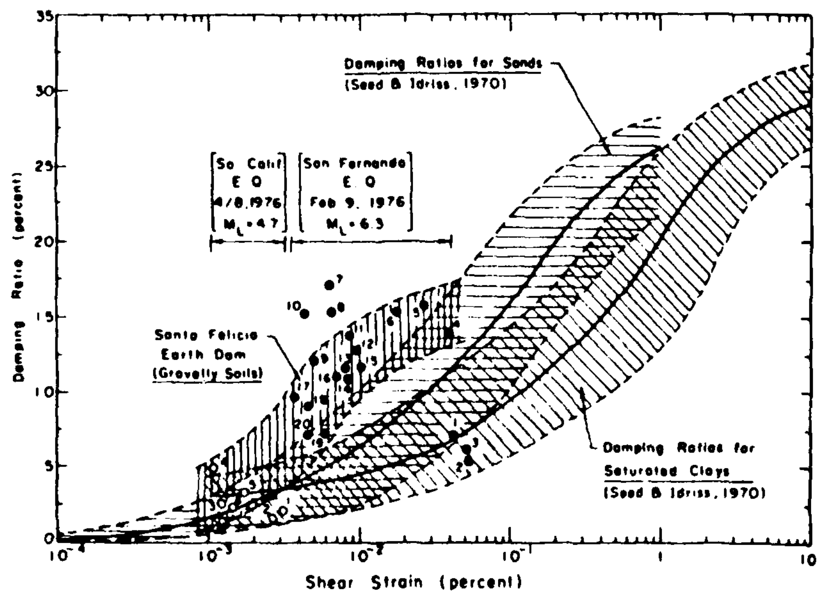
35. Abdel-Ghaffar, A.M., and Scott, R.F. (1979) Shear moduli and damping factors of earth dam, J. Am. Soc. Civ. Engrs., Geotech. Engrng. Div., 105(No. GT12):1405-1426.

36. Sidey, R., Marti, J., Rodriguez, L., and White, D. (1980) Borehole Shear Device Feasibility and Preliminary Studies, NTIS Accession Number AD A090697, Final Report, Dames and Moore for U.S. Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico.



a)



b)

Figure 19. (a) Modulus reduction curves, and (b) Damping factors, obtained by inversion of strong-ground-motion data at an earth dam (Abdel-Ghaffar and Scott[35]).

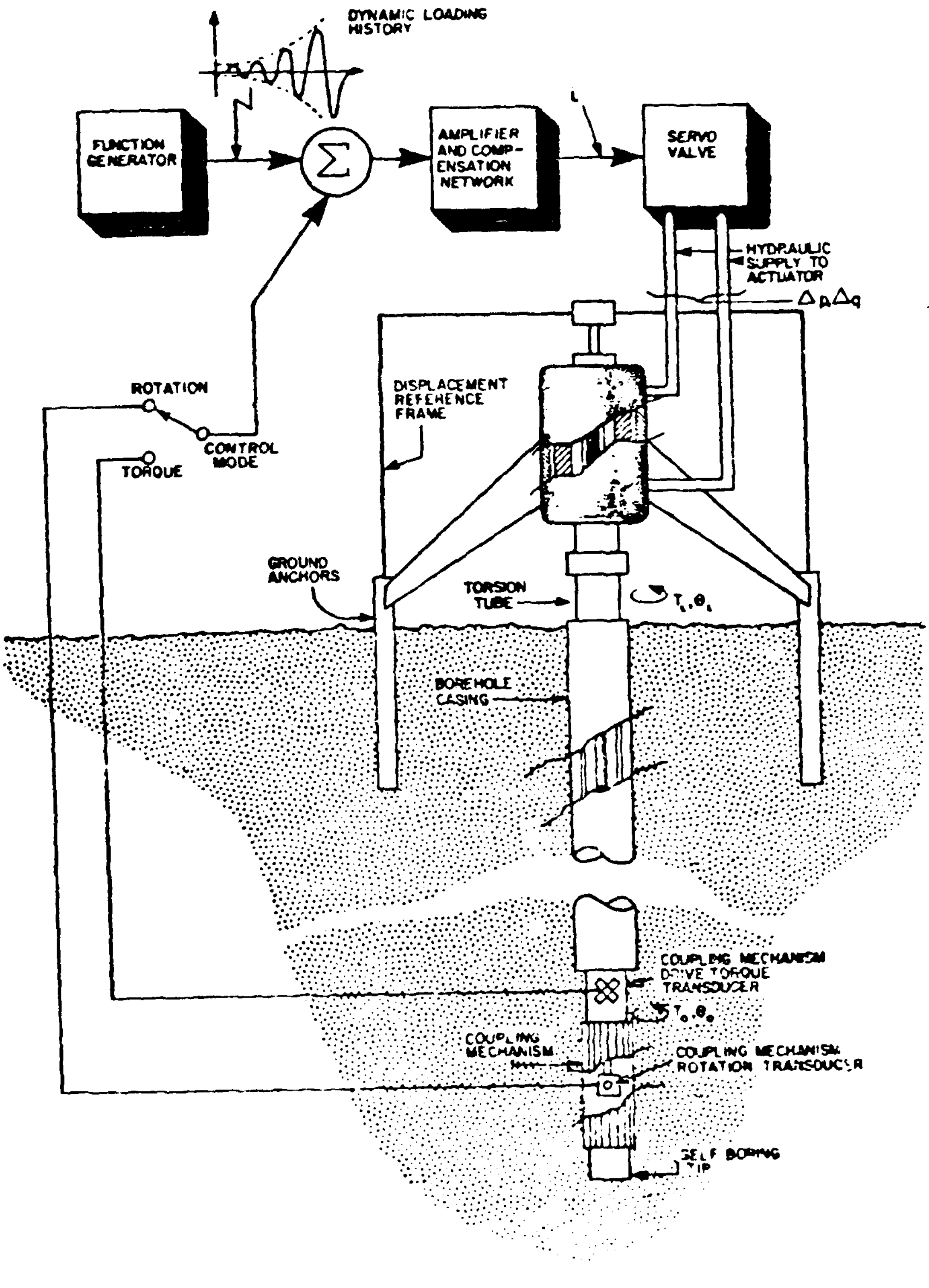


Figure 20. Schematic representation of the Borehole Shear Device (Sidey et al[36]).

4.4 Static Loading and Ultimate Strength Methods

Static loading and ultimate strength methods form the third general class of procedures presently used for in situ property determination. These methods differ from the previous two general classes of in situ techniques in that:

(1) the soil is normally loaded to failure; and
(2) the soil response is generally recorded during loading only: Hence no cyclic stress reversals occur.

These methods are limited in their ability to simulate earthquake loading conditions. They may, however, be useful to define an asymptote for dynamic stress-strain curves at high strain levels or to locate yield surfaces for elastic-plastic soil models.

Static loading methods involve applying a known load to the soil and monitoring the soil response, usually in the form of deformation. These methods include: pressuremeters, in which increasing stresses are applied to the walls of a borehole and the resulting volume change monitored; vane shear tests, in which a multi-bladed vane is inserted into soil to the depth of interest and then twisted at a constant rate while monitoring the torque; and plate bearing methods, in which a gradually increasing load is applied to a rigid plate, either on the surface or down a borehole, while monitoring the resulting deformation of the soil.

Ultimate strength methods involving forcing a tube or a cone into the ground and counting the number of blows required to advance the device a specified distance. This information is then used along with empirical relationships to estimate the strength of the soil. An example of an ultimate strength technique is the Standard Penetration Test (SPT), consisting of a cylindrical tube which is driven into the soil using a hammer. The SPT procedure is conducted by counting the number of blows required to drive the sampler 18 inches. The number of blows to drive the sampler the last 12 inches are reported as the N-value or blowcount. The blowcount is used to estimate material properties at the site.

4.5 Summary

Each of the three general classes of in situ methods described above to determine dynamic soil properties has its advantages and disadvantages.

Advantages of the seismic wave propagation methods are that they provide an estimate of soil properties over a large volume and can be used to estimate soil properties over a range of depths. The major disadvantage with seismic wave propagation methods is that they only operate in the low strain regime unless the receiver is very close to the source. This problem is avoided with the dynamic loading methods, since the soil properties are measured at the exciting mechanism; but as a corollary these methods only provide information on soil properties over a limited region around the source. Static loading and ultimate strength methods are limited in their relevance to site response studies, but can provide useful complementary information in conjunction with one or more of the other techniques.

5. CONCLUSIONS & RECOMMENDATIONS

The ultimate goal of this project is to investigate the feasibility of using measurements of microseismic activity at a particular site to predict the high strain response under earthquake loading conditions. In Section 1 we saw that, in order to do this, the dynamic properties of the soil column at the site must be determined under a wide range of loading paths. The use of laboratory studies to accomplish this goal is suspect because of demonstrated uncertainties due to sample disturbance and possible differences between the laboratory and in situ states of stress. Determination of dynamic soil properties via in situ methods is therefore preferred.

In Section 4, various in situ techniques for determining shear moduli and damping in the strain range from 10^{-6} to 10^{-3} characteristic of earthquake loading were described. Each of these methods has its advantages and disadvantages so that the use of several methods is indicated.

Figure 21 shows two examples of wave propagation techniques that can be used to provide information on dynamic soil properties at high strains and as a function of depth in the soil column. In the VSP technique, clamped

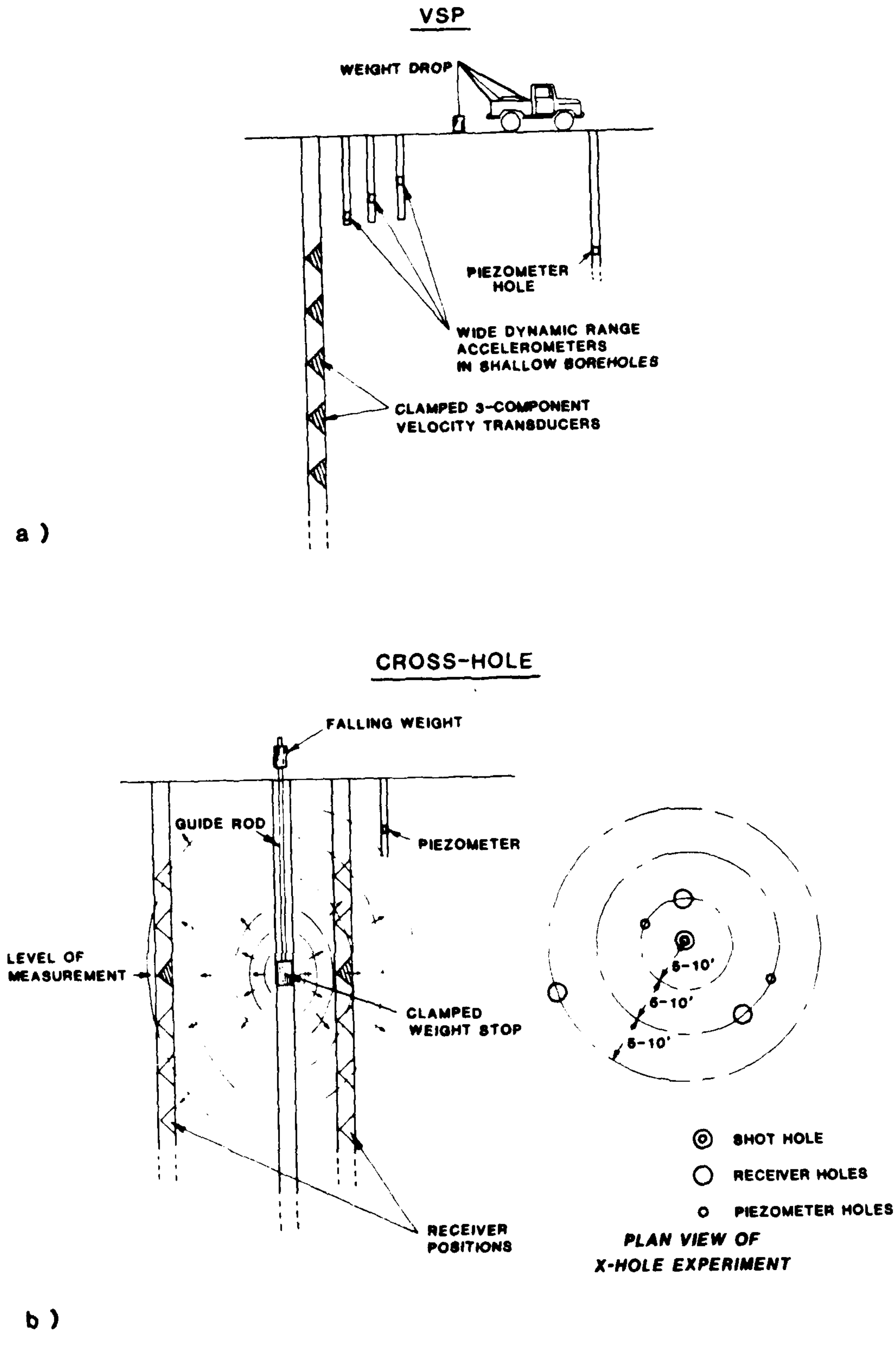


Figure 21. Examples of seismic wave propagation techniques.

three-component velocity tranducers down a borehole give information on compressional wave velocity as a function of depth. In the high strain region near the surface wide-dynamic-range accelerometers should be used to measure the response of the soil. In order to monitor pore pressure variations during the experiments, a piezometer should be emplaced in the soil column in a separate hole.

Upon replacing the clamped velocity tranducers with hydrophones in the receiving borehole, a hydraulic VSP survey can be run, which may provide information on the relative permeability of various layers within the soil column.

The design of the cross-hole experiment shown in Figure 21 incorporates the design results of Shannon and Wilson[28] and can be used to determine shear moduli in the strain range of 10^{-6} to 10^{-3}. It is preferable to locate the receiver holes on a concentric plan as illustrated in Figure 21 to avoid possible disturbances in the wave field at one borehole caused by drilling the other holes. A clamped weight-drop device can be used to impart strong shearing motion to the soil, hence allowing values of shear wave velocity and shear modulus to be determined. By replacing the falling weight in the cross- hole experiments with a vibratory source clamped to the guide rod, it should be possible to induce vibratory motion at different depths in the borehole using the same clamping mechanism. Thus information on the soil behavior under varying cycles and frequencies of loading can be obtained.

Analysis techniques for the cross-hole technique can involve the measurement of seismic wave velocities, thus providing information on variations in shear modulus, and waveform-fitting techniques, from which some estimate of damping in the high strain regime can be obtained (Fugro[8]).

For reconnaissance purposes, the surface methods of seismic refraction and reflection can be used to determine the properties of different layers within the soil column.

All of the above techniques utilize concepts that have been tested and demonstrated in the field. Care must be taken in measuring the inclination of the boreholes, and advanced techniques for interpreting the data are required in the high strain regime near the source. However, the techniques for doing this are known.

Other techniques that are available for high strain dynamic soil measurements at depth include dynamic response methods such as the dynamic screwplate device described by Andreasson[31] and, possibly, the Borehole Shear Device described by Sidey et al[36].

In summary, by careful application of a variety of in situ techniques, it should prove possible to determine the dynamic soil properties of soils in situ under the types of loading conditions that may be experienced during earthquakes.

Turning to the question of how these measurements may be used to predict the high strain response at a site using measurements of microseismic activity, we refer to the work of Akamatsu[3], who analyzed measurements of microseisms at two sites in Japan. Figure 22 displays amplitude spectra as determined from the vertical and two horizontal components of motion recorded at two sites: SUM, located on a hard rock outcrop; and INST, located in an adjoining soil basin. The upper series of curves in Figure 22 show the amplitude spectra obtained during a period of strong microseismic activity following passage of a typhoon over the nearby coast; whereas the lower set of curves correspond to calmer conditions recorded following the typhoon. Akamatsu[3] formed the ratio of these two spectral curves and this is shown as the single line in the lower part of each set of plots. The spectral ratio curve demonstrates that the level of microseismic activity measured in the soil basin is amplified, particularly at higher frequencies, compared to the measurements made on the adjoining hard rock site. In addition, Figure 22 shows that the shape of the spectral ratio curve is independent of the strength of the microseismic activity. Akamatsu[3] also computed spectral ratio curves at the same two sites for microseisms generated from several distant earthquakes. He obtained essentially the same spectral ratio curves as shown in Figure 22.

These results suggest that the response of a soil column to microseismic activity is independent of the amplitude and source of the microseisms. If information on the dynamic properties of a particular soil column were available as a function of strain level, simple scaling rules might therefore be developed that would allow the prediction of high strain response using low strain field measurements. Because of increasing complexity in the source function for earthquakes of increasing size, this conclusion is at present speculative. There is, however, a direct way to test these ideas. This is to perform dynamic site measurements in places where strong motion data from earthquakes of

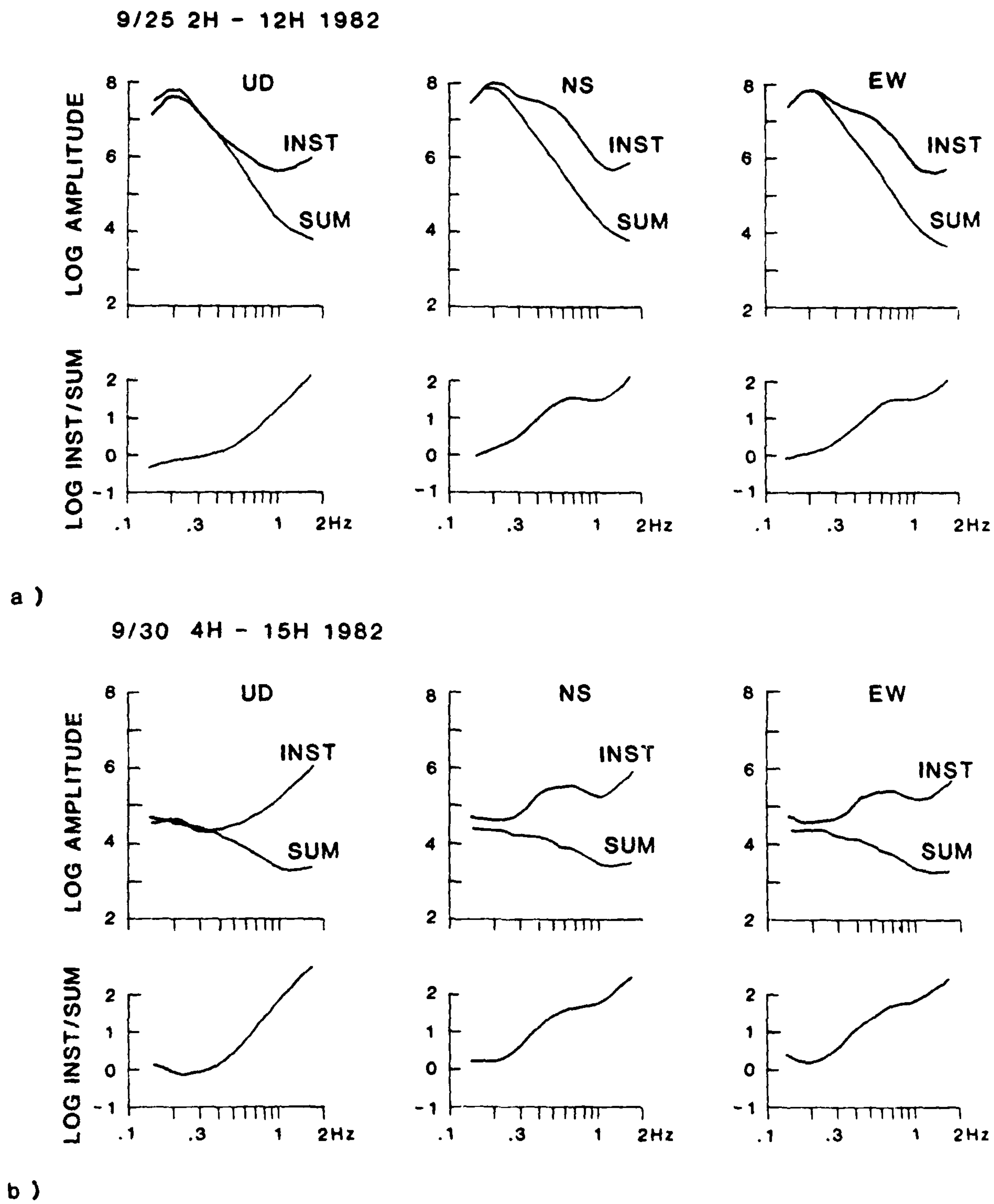


Figure 22. Amplitude spectra and spectral ratios (INST/SUM) from wave-generated microseisms recorded at a hard rock site (SUM) and in an adjoining basin (INST) in Japan (Akamatsu[3]) (a) during a storm (b) after a storm.

different magnitudes and epicentral distances are available. Dynamic properties of the soil column at the sites, as inferred from in situ measurements, could be used to predict the strong motion response using measurements of microseismic activity. Direct comparison of the predicted and observed strong motion records should then indicate the potential of this approach. We propose as part of our Phase II work to carry out such a test at two sites in the Western U.S.

We conclude that the goal of using microseismic measurements to predict the high strain response at a site is best approached through development of in situ techniques to determine the dynamic soils response under earthquake loading conditions. With this information, it may then be possible to develop certain scaling rules which can be used to modify microearthquake response spectra to accommodate non-linear soil behavior under high-strain conditions.

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